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Towards Enabling Human-Robot Collaboration In Industry: Identification Of Current Implementation Barriers

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Abstract

Human-robot collaboration (HRC) is designed to combine the repeatability and precision of robots with the flexibility and adaptability of human workers. However, despite being researched for several years, HRC applications are still not broadly adopted in the industry. This study aims to identify current barriers to HRC adoption in the industry from a practical perspective. Therefore, a qualitative explorative approach based on semi-structured interviews with knowledgeable industry experts was chosen. The study was conducted in cooperation between IMT Nord Europe and the Technical University of Munich in France and Germany. Thereby, several experts from various backgrounds in areas such as robot manufacturing, system integration, and robot application in manufacturing were interviewed. These interviews are inductively analysed, and the findings are compared to the state-of-the-art in scientific HRC research. The study offers insights into the practical barriers to HRC adoption resulting from the technical, economic, social, and normative dimensions as well as the trade-offs between them. Based on these insights, opportunities for future research are identified.

Keywords

Robotics; Human-robot collaboration; Implementation barriers; Industry survey

1. Introduction

The increasing complexity and rapidly changing demands in the industrial sector have emphasised the need for more efficient and flexible manufacturing systems. The term human-robot collaboration (HRC) describes approaches that combine the strengths of human workers, such as adaptability, flexibility, experience, and problem-solving skills, with the precision and repeatability of robots [1,2]. These systems can support humans when performing physically challenging tasks and simultaneously allow automation in scenarios considered unfeasible previously [3]. Resulting work environments can be more efficient, safer, and more productive [4]. Another motivation for the use of HRC is the opportunity it offers to address skilled labour shortages, e.g., [5].

Generally, HRC applications are divided into three categories based on the spatial delineation of humans and robots [2,6]. In coexistence scenarios, robots and humans may share the same workspace, but not simultaneously. In cooperation scenarios, they stay in the shared workspace at the same time but do not work on the same workpiece. Finally, in collaborative HRC applications, humans and robots also execute tasks on the same workpiece. In this context, the term cobot refers to lightweight robots equipped with additional

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force-torque sensors that are specifically designed to reduce risks of injury. In this work, the term HRC may also involve deploying classical industrial robots in HRC applications or use cases involving mobile robots deployed in presence of humans.

Despite the numerous potentials of HRC, its adoption in the industry is still slow. Various barriers, including technical, economic, social, safety, and organisational factors, have prevented or slowed the implementation of HRC in real-world applications [7]. To help overcome these barriers, this study deploys a qualitative research approach based on semi-structured interviews with experts from industry, to understand existing practical barriers and their underlying causes in more detail and propose directions for further research.

To illustrate our findings, the study is organized as follows. Section 2 discusses related works on the challenges of HRC. The study's methodology is described in Section 3, including data collection and analysis. The derived results are presented in Section 4, including a discussion of their implications. Finally, Section 5 summarises and concludes the paper.

2. Related works

Different challenges to implementing HRC applications have already been identified in scientific literature. In the following, findings of works summarising these challenges are presented at first. Afterwards, studies that already involve industry experts are highlighted.

Authors in [8] conducted a semi-structured literature review to analyse the challenges of HRC implementation, identifying twenty challenges, including initial investment costs, flexibility concerns, scalability issues, and operator training. The identified challenges were then validated by an expert panel. In contrast, [9] review HRC solutions proposed in the literature and summarise open challenges for HRC in five categories. They identify the handling of the systems' overall complexity (1) as essential for adopting HRC in the industry. Due to HRC's safety requirements (2), the technical complexity is further increased. Furthermore, they emphasise that safety does not only have a technical or normative aspect but that the operators' confidence (3) in the system's safety must be considered, too. Finally, the accessibility (4) and flexibility (5) of HRC should be improved, keeping industrial use cases in mind. The emphasis on safety is shared by [10], including the distinction between technical safety and perceived safety by the operator. Standards governing technical safety are continuously evolving. In this context, the high complexity of the environment is a major challenge, especially since it is more difficult for humans to predict the industrial robots' movements, e.g., compared to vacuum cleaner robots with fewer degrees of freedom. Communicating the motions to the operator can improve and increase the operator's confidence in the system's safety. On the other hand, human motion prediction is also a challenge to HRC applications' safety [11]. Moreover, human motion prediction is essential for effective function distribution between humans and robots. Therefore, [11] name safety, effectiveness, and complexity as the main challenges for HRC solutions. In contrast to the previous studies, [12] specifically investigated the challenges of HRC in the shipbuilding industry. Among other things, human unpredictability is highlighted as a challenge. However, industry-specific challenges, such as high load capacity, and general challenges, such as ergonomics, e.g., workers' posture and part weights, during execution, are also identified. Authors in [13] examine the challenges associated with processing and analysing the large volumes of data produced by cyber-physical systems, including those in HRC, underlining the complexity of scheduling tasks within Industry 4.0 contexts. To encapsulate the broader context, [14,3] discuss the application of HRC in various manufacturing processes, noting that the balance of task distribution between humans and robots often depends on specific contexts such as part weight, size, ergonomic considerations, and visibility. This introduces an additional layer of complexity when addressing the challenges in one-way and two-way human-robot collaboration [14].

Shifting the focus to specific aspects of HRC, [15] investigate the economic aspects of HRC line balancing along the dimensions of assembly line characteristics, collaborative assumptions, and methodology. Authors claim that research has focused on linear assembly lines where humans and robots collaborate sequentially rather than in parallel. As mentioned, human unpredictability is a major challenge, resulting in non-deterministic task execution times. One way to counter human unpredictability is to use real-time data acquired via Industry 4.0 networks. It is further pointed out that ergonomic aspects should be considered in an economic analysis. According to [16], identifying universal economic challenges for HRC is particularly difficult due to the significantly varying applications. [17] point out that learning processes used by robots for interacting with humans and different environments may pose a critical aspect to consider when designing and implementing HRC applications. [18] investigate the effect of HRC applications on the involved human workers within a scoping literature review. Considering the categories ergonomics, safety, and productivity, the inseparability of the actual and perceived properties could be shown from a psychological perspective. Therefore, stress, workload, acceptance, trust, and usability should be considered when analysing an application's psychological effects. [19] add the robot's behaviour, the user's self-efficacy, and the operator's experience working in HRC systems as criteria, which were identified via a systematic literature review. In turn, integrating the operator experience into HRC application design and testing is described as the main challenge.

While the previously mentioned studies are mainly based on scientific literature, others already specifically include industry perspectives and therefore focus more on the practical challenges of implementing HRC in industry. In [20] such challenges are identified based on a questionnaire, supplemented by five expert interviews. Challenges are categorized into safety-related, organisational- and process-related, and technical aspects. [21] focus on challenges for small and medium enterprises, incorporating interviews with practitioners from five companies. The main challenges identified are related to safety, performance, strategy, involvement, and training aspects. A case study in a Swedish heavy vehicle manufacturing company using the actor-analysis method is performed by [22]. During this process eleven employees with different roles in the company were interviewed concerning their experience with HRC implementation. Authors conclude that safety-related issues and under-development standardization are the key challenges for HRC adoption. [23] on the other hand focus on risk assessment challenges, conducting multiple expert interviews, followed by a questionnaire. Their fragmentation, complexity, and a lack of validation are listed as the main shortcomings of existing approaches for HRC risk assessment.

To facilitate the practical adoption of HRC, developed methods and solutions must be based on a profound understanding of current implementation barriers. This understanding can only benefit from the inclusion of practical insights. Works like [20,23,21,22] already contribute to this goal. Nevertheless, further studies are necessary to validate and extend previous findings and gather a holistic understanding of underlying phenomena.

3. Methodological approach for identification of barriers to HRC adoption

To investigate what barriers to HRC adoption exist in the industry, an explorative qualitative research design was chosen based on a multiple case study. Semi-structured, in-depth expert interviews served as the primary data source. These interviews were afterwards inductively analysed to yield new insights. Since HRC is not yet broadly adopted in industry and the reasons for this are not fully understood so far, qualitative research is adequate to assess underlying phenomena holistically [24]. Additionally, these phenomena may span a wide range of aspects that are not only technical but may also be economically, socially, or organisationally caused. Case studies are well suited to generate new knowledge about novel topics [25] and answer questions such as *what is happening?*, *how is it happening?*, and *why is it happening?* [26,27]. Multiple case studies usually produce more robust results in this context than a single case study [28].

3.1 Data collection

As mentioned above, we chose to use semi-structured, in-depth interviews with multiple knowledgeable experts from the industry as our primary source of data. Such interviews are a popular technique in qualitative case studies and are used as such in this study [26]. Members of organisations experience occurring phenomena directly and can provide first-hand insights [29]. The experts usually have long and diverse backgrounds in their specific fields. Since it is unlikely that the interviewers will influence multiple experts in the same way, the danger of introducing bias into the study is reduced [28]. Experts from different companies were selected based on their experience and their position. These companies operate in various business fields as robot manufacturers, system integrators, or application users. Furthermore, we did not only focus on scenarios involving stationary robots but also explicitly included experts in the fields of mobile robotics. This allows for an assessment of discrepancies and similarities between these applications. The interviews were conducted in German and French language, and anonymity was assured to all experts. Subsequently, all the recorded contents were accurately translated into English for analysis, maintaining the authenticity and essence of the interviewee's responses. We used an interview guideline to give the interview process a standardised structure. This guideline was iteratively reviewed and improved before the first interview, to avoid leading the witness questions and anticipate related questions that may come up during the interviews [29]. However, following the principles of flexibility and openness, we deviated from it, if appropriate, to react to the experts' interests and knowledge [29]. The full interview guideline can be found in Appendix A.

3.2 Data analysis

The interview analysis was conducted following the systematic approach to inductive analysis developed by [29]. The methodology is based on summarising the content step-by-step into a data structure [29]. First, the interview recordings were systematically assessed and the core messages, hereafter referred to as first-order concepts, were filtered out. In doing so, the semantics used by the informant were retained as far as possible, and a certain distance from the literature was kept to avoid confirmation bias [29]. In the second step, the first-order concepts were grouped into categories. These categories are hereafter referred to as second-order themes. The concepts were compared, examined for similarities and differences, and thus progressively categorised. This process was highly iterative. In the third step, the second-order themes were further grouped into so-called aggregated dimensions. We repeatedly involved feedback from external but knowledgeable colleagues to discover potential misinterpretations and contradictions and to validate our interpretations [30].

4. Results

In the following section, we first give an overview of the expert sample. Afterwards, the findings of the study are presented and discussed.

4.1 Sample characterisation

The sample for this study comprises eleven experts with diverse backgrounds and experiences in the field of HRC. An overview of different aspects describing the sample is provided in Figure 1. Experts' years of experience in the industry range from one to over 25 years, offering a wide variety of perspectives. The companies they represent generate revenue between one and several thousand mil. EUR, emphasising the sample's diversity in terms of company size and financial results. The participants specialise in various focus areas, such as robot manufacturing, system integration, and application usage. This diversity allows for a comprehensive understanding of the barriers to HRC adoption in manufacturing systems. It should be noted, however, that the sample in this case does not claim to be a representative sample of the population, as is the case with quantitative studies. To measure the current importance of HRC in their organisations, the interviewees were asked to rate its relevance on a scale from one (very low) to five (very high). The current relevance of HRC among interviewees varies, with scores ranging from one to five and an average score of 3.6. The experts anticipate a higher relevance of HRC in the future, with scores ranging from three to five and an average score of 4.4, indicating some sort of familiarity with the subject.

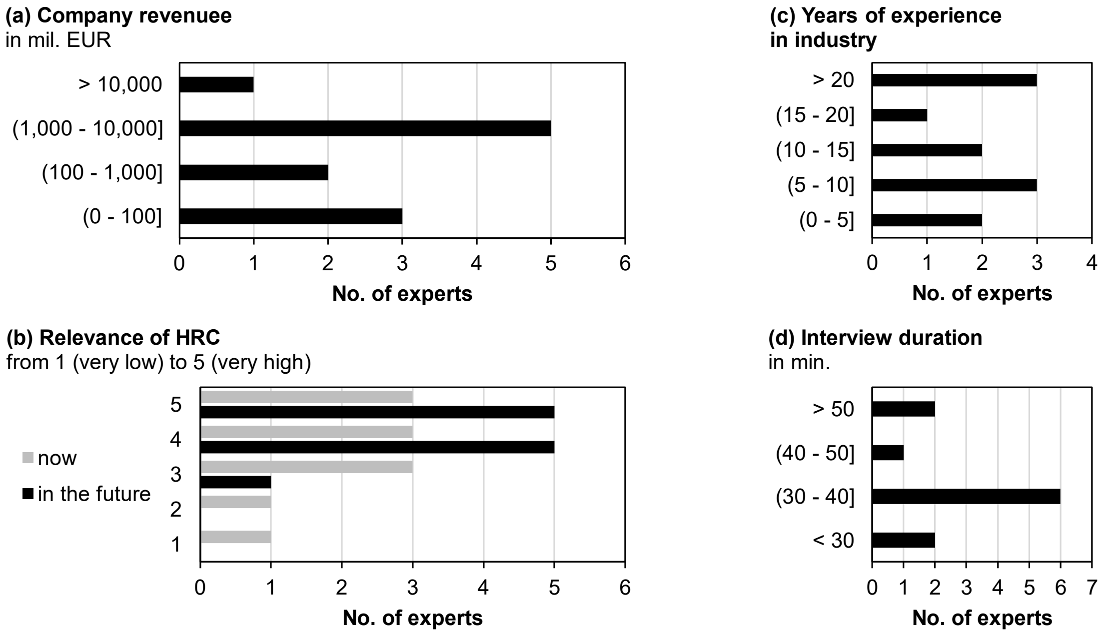

Figure 1: Characterisation of the sample, including company revenue (a), years of experience in industry (b), the duration of the interviews (c), and the perceived relevance of HRC now and in the future (d)

4.2 Presentation of results

In total, 240 first-order concepts were extracted from the interviews and grouped into 23 second-order themes. Based on these 23 second-order themes, four aggregated dimensions could be identified: *1) technical*, *2) economic*, *3) social*, and *4) norms and safety*. All of the second-order themes either specifically address a single dimension or address a relationship between two of the dimensions. No differences could be observed between Germany and France when merging the second-order themes into the four aggregated dimensions. Therefore, the results presented are valid for both countries. In the following, we first report on findings regarding individual dimensions before focusing on their interrelations. A full list of second-order themes and their associated aggregated dimensions is provided in Appendix B.

4.2.1 Aggregated dimensions

Regarding the *technical* dimension, multiple experts reported on the need for HRC applications to be capable of handling complex environments. This requires sensor systems to perceive the environment and adapt the robots' behaviour accordingly.

Second-order themes addressing the *economic* dimension focus on the profitability of HRC applications. While on the one hand, the flexible integration of HRC systems into assembly lines allows for an increase in overall profitability. On the other hand, HRC's higher development costs and efforts, combined with non-deterministic processes during production, often result in an insufficient cost-performance ratio of HRC systems.

"I believe that the foundations have been laid regarding the robots, but now we need an overall view of how to achieve a productive system quickly." (interview no. 3)

When exploring the *social* dimension, several experts emphasise the importance of acceptance and interaction between human workers and robots. As the robot's autonomy increases, so does the need for appropriate social behaviour since the success of the application may also depend on the workers' perceptions and willingness to collaborate. This includes respecting personal space, using non-verbal cues, and being predictable in its movements. In turn, workers may need additional training to efficiently interact with collaborative robots.

Regarding *norms and safety*, experts perceived the normative landscape as complex and ambiguous, which poses a challenge during the development of HRC applications. Different stakeholders interpret the guidelines differently, and a strict interpretation makes realising HRC applications difficult.

"There are no clean standards here [in Germany] that you can use to develop well and reach your goal quickly." (interview no. 1)

4.2.2 Interrelations between aggregated dimensions

Most of the second-order themes (14 out of 23) addressed two aggregated dimensions, describing some sort of relationship between them. The following section will focus on these relationships between dimensions.

Technical and *economic* aspects were addressed by four themes. One barrier in this context is that competitive HRC applications are usually technically complex. Required sensors and safety features result in high development efforts, rendering HRC applications less attractive economically. Different experts also stressed the importance of assessing potential use cases' suitability for an HRC solution. For several use cases, classical industrial robots are better suited, e.g., when short cycle times are necessary or ensuring safety is technically very difficult, e.g., when collaboratively handling objects with sharp edges. This is caused by the robot being stopped when a collision potential between a robot and a human worker is detected and results in non-deterministic cycle times. Therefore, more focus should be put on approaches that specifically avoid collisions rather than reduce their impact. Overall, HRC solutions may benefit from new application and development paradigms.

"The wish was to design the solution as before and then just add HRC to get rid of the protective fences, and that just doesn't work. In fact, you have to look at it holistically [...]. Otherwise, you create facts through the application realisation, which you cannot handle from the HRC point of view." (interview no. 2)

One of the main reasons for the *technical* complexity of HRC applications was found in *safety* requirements. A coexistence scenario is considered more technically feasible and economically more reasonable than full collaboration. It was also mentioned that safety-certified hardware is usually less powerful, and system intelligence functions are separated from safety functions. This leads to conservative behaviour and frequent stops of the robot.

That cobots often come with intuitive graphical user interfaces is a *technical* aspect that also affects the *social* dimension. That easier programming interfaces make robots more accessible for non-experts is viewed as a benefit.

Two themes have been identified that show the interaction between *safety* and *economic* aspects like performance, adaptability, and flexibility of applications. Safety requirements affect an application's performance by effectively limiting payload and movement speed and, respectively, cycle times. Consequently, HRC applications cannot always execute a process step profitably. In addition, conservative safety systems ensure worker safety by changing the robot's trajectory, reducing its speed, or stopping it. The resulting unpredictable cycle times impair the production flow and, consequently, the production line's economic efficiency.

"The topic of speed also came up with many who had originally planned [an HRC application]. You eventually realise: I can't calculate with the usual accelerations or cycle times if I want to realise HRC." (interview no. 4)

While the discussed effects may lead a company to decide not to use an HRC application, aspects like adaptability and flexibility may also complicate the development of an HRC application as they increase the system complexity. In turn, it is necessary to unify two complex systems, i.e., the automation of an assembly step and the safety devices. As a result, HRC applications are usually only transferable to another task to a limited extent.

The relationship between the *social* and *economic* dimensions highlights the benefits of improved working conditions for workers in HRC applications. Ergonomic conditions can be improved, and workers may be relieved of strenuous tasks and assigned to higher-value tasks. However, experts also pointed out the current lack of consideration for these aspects in economic evaluation. This may also be due to the fact that there are few metrics to include improved working conditions in economic evaluation.

"We have noticed that these ergonomic aspects are usually not directly taken into account economically. Many companies do not include such aspects in their calculations but instead focus directly on the ROI." (interview no. 2)

The complex *norms* for HRC affect the *social* aspects since the development of such applications depends heavily on specialised experts. Furthermore, it is important to critically evaluate the intersection of *safety* requirements and *social* interaction potential. Although, seamless interaction between humans and cobots is desired, prioritising human worker safety entails strict adherence to established safety regulations to mitigate workplace accidents and injuries. Constructing a secure operating system and adequate human-robot interactions requires considering various parameters, such as risk assessments, safety protocols, user training, and intuitive interfaces.

"The safety aspect is also a stumbling block, as customers want a mobile robot to be very close to humans (for example, at 10 cm), whereas this distance does not comply with the norms and safety standards for this type of solution." (interview no. 10)

In conclusion, the interrelations between the identified dimensions are manifold, and a clear assignment to two individual dimensions is often difficult. Furthermore, a large portion of barriers is due to some kind of trade-off between two or more dimensions, describing features that cannot be completely fulfilled simultaneously.

4.3 Discussion of results

The findings of our study underline aspects presented in the existing literature. These include the high level of technical complexity in HRC applications due to required safety functions and the complexity of the environment [11,10,9]. Barriers in the economic dimension also match those identified in previous studies, like high investment costs for HRC systems, reduced productivity, and non-deterministic cycle times [8,15] or insufficient flexibility and scalability of HRC applications [8,9]. Regarding social aspects, interviewed experts also pointed out the need for training and early integration of users into development processes to increase system acceptance, as mentioned by [19,18]. In the eyes of some experts, however, user acceptance did not represent a significant barrier but rather an aspect that can be well addressed through the mentioned measures. Apart from confirming and extending already identified barriers in the literature, our study also sheds light on the interrelations between different aspects and their trade-offs. Understanding these trade-offs in more detail may play a crucial role in overcoming current implementation barriers for HRC.

We conclude that one of the main barriers to industry application is the insufficient cost-performance ratio of HRC systems, which makes them economically unattractive. The safety requirements can be fulfilled by technical solutions, like integrating sensors or lightweight structures. Still, these increase the system complexity and, therefore, development costs or lead to reduced process speed and payload and therefore reduce a system's productivity. A company's decision is usually based on monetary aspects, and the gained advantages, like the fenceless operation of the robot, may not be enough to compensate for these disadvantages. Furthermore, ergonomic advantages of HRC approaches are usually not included in such monetary calculations [31]. Based on this conclusion, several starting points for research are suggested:

Use case assessment: As individual experts pointed out, HRC solutions are often not competitive when simply substituting a classic robot application. Additionally, in collaborative scenarios, a cobot will not substitute a human worker completely at a particular station. If the automation goal is to actually reduce the required number of human workers for a task, multiple workstations must be addressed. Therefore, the assessment of a use case regarding its suitability for HRC plays a crucial role for successful implementation, as also mentioned by [20]. This also concerns the non-deterministic cycle times of HRC applications.

Collision avoidance: As different experts pointed out, past solutions may have focused too much on reducing the impact of collisions rather than avoiding it. Such active collision avoidance may enable increased robot speeds and payloads. Active collision avoidance strategies can be employed, leveraging advanced technologies such as computer vision and human movement anticipation.

Scalable safety systems: Safety systems that can be easily transferred to another robot application may reduce system complexity and therefore development costs. Such systems should be easy to integrate with the robot and other peripherals. This may also increase the flexibility of an existing system to handle different tasks.

Reduce development efforts: Since a current drawback of HRC solutions is their high development cost, reducing these costs is of great importance. During the study, different approaches were identified. On the one hand, a higher degree of modularisation of components is desirable, e.g., by combining sensors with preconfigured software for analysis. On the other hand, experts also suggested methodical approaches, that may help to structure the development process and reduce the dependency on the experience of HRC experts. Easy programming interfaces and methodologies can contribute to the reduction of development efforts.

5. Conclusion and outlook

To shed light on current barriers to adopting HRC in the industry, a multiple case study based on semi-structured expert interviews was performed. Eleven interviews with experts from France and Germany were conducted and analysed. The identified barriers could be associated with the technical, economic, social, and safety dimensions. We found that many aspects brought up by the experts address interrelations and trade-offs between these dimensions, such as between safety and technical or technical and economic aspects. To advance the adoption of HRC and overcome these barriers, several research and development questions were proposed. These include exploring technical innovations for collision avoidance and safety systems or developing more cost-effective strategies.

By addressing these research directions, future studies and applications can contribute to the effective implementation of HRC in industrial settings. This may unlock the benefits of increased productivity, improved working conditions, and optimised performance. It is crucial to take a holistic approach and consider the multidimensional nature of HRC to realise its full potential.

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Appendix

A. Interview guideline

1. **Professional background**
   - What is your current job or position in your company?
   - Please explain your role and responsibilities.
   - Please report on your professional career (incl. training, apprenticeship etc.).
   - How long have you worked in your current position?
2. **Clarifying the term human-robot collaboration (HRC)**
3. **Experience with HRC applications in past, current, or planned projects**

   3.1. Importance
   - How important is HRC for your company, rated on a scale from 1 to 5 (1 = very low; 5 = very high)?
   - How important will HRC be for your company in the future, rated on a scale from 1 to 5 (1 = very low; 5 = very high)?

   3.2. Specific for HRC users
   - Did you or are you currently planning to realise an HRC application?
   - Which use cases for HRC applications do you know or can imagine?

   3.3. Specific for system integrators
   - Could you report on your typical HRC implementation projects, including workflows?
   - What are the most common HRC applications of your customers?

   3.4. Challenges of HRC implementation
   - Do you have an example of a project where an HRC application was considered, but another solution was selected?
   - If yes: Why did you choose another option?
   - If yes: Which technology/application was selected instead?
   - If yes: Would you decide differently with today's technical and business constraints?
   - If yes: At which point does the current situation differ from the situation of the past?

   3.5. Social factors and staff opinion (planning and workshop staff)
   - What is the attitude of the workforce towards HRC?
   - Did the staff's attitude towards HRC change over the curse of the HRC project execution?
   - Is there a difference in the attitude towards HRC between planning and workshop staff?
   - Is there a difference in the attitude towards HRC in the groups which do work with HRC solutions and those that don't?
4. **Identification of HRC barriers/inhibitors**
   - What barriers to HRC exist?
   - Could you please order the aspects according to their relevance?
5. **Identification of potential future enablers and innovations**
   - Which of the mentioned obstacles or problems must be overcome to use HRC more extensively?
   - Which technologies can be helpful or are a prerequisite?
   - What could be the next innovation leap or game changer, in your opinion?

B. Second-order themes and associated aggregated dimensions

Second-order themes	Technical	Economic	Social	Norms & safety
– Use case suitability assessment	X	X		
– Competitive HRC applications are technically complex	X	X		
– New application and development paradigms required to reach full potential	X	X		
– Increased productivity by collision avoidance	X	X		
– HRC lowers the burden for robot usage	X		X	
– Decreased performance of certified hardware	X			X
– Trade-off between system capability (intelligence) and safety	X			X
– Distinguish coexistence and collaboration	X			X
– Safety as a system complexity driver	X			X
– Capabilities to handle complex environments	X			
– Advantages beyond monetary aspects		X	X	
– Trade-off between performance (speed and payload) and safety		X		X
– Trade-off between adaptability/flexibility and safety		X		X
– Flexible integration into shopfloor		X		
– Higher development costs and efforts		X		
– Cost-performance-ratio insufficient		X		
– Non-deterministic processes (e.g., cycle times and ROI)		X		
– Specific know-how during development required			X	X
– Human safety is imperative for interaction			X	X
– Training for HRC application user			X	
– Data privacy concerns			X	
– No lack of technology enthusiasm			X	
– Complex and ambiguous norms and regulations				X

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