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Quality Function Deployment (QFD) for human-robot collaboration (HRC): Systematic selection of key performance indicators in HRC

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Abstract

Human-Robot Collaboration (HRC) has received significant attention in research, yet the assessment of successful implementations remains challenging. Reasons for the limited spread of HRC include technological limitations, safety concerns, lack of standardization, potential workforce resistance, regulatory issues, and the complexity of human tasks. Lacking standardized measurement criteria, coupled with a lack of systematic evaluation approaches, make it difficult to thoroughly assess the deployment of HRC scenarios. To address these limitations and facilitate management decisions, this paper introduces a decision-making framework. The framework focuses on the evaluation and ranking of potential HRC-key performance indicators (KPIs), by using Quality Function Deployment (QFD). By integrating the identified KPIs with the requirements of process owners, the framework aims to enhance the systematic assessment of HRC implementations, providing valuable insights for continuous improvement initiatives.

Keywords: human robot collaboration (HRC); key performance indicators (KPI); quality function deployment (QFD); process orientation

1. Introduction

Advancing trends like mass customization and mass personalization increase manufacturing complexity. Hence, more changeable and flexible manufacturing systems are required. Combining human flexibility with robotic repeatability is a promising way to achieve the required flexibility in manufacturing, called human robot collaboration (HRC) [1]-[4]. Its highest potential is judged in the assembly process, given the predominantly manual nature of assembly lines [3,4].

However, even though HRC is widely discussed in literature, few successful implementations in practice exist. Major challenges in HRC implementation include the individual risk assessment and application of norms in practice [3]. Incorrect usage can reduce the worker's trust and decrease productivity in HRC-system. To thoroughly evaluate the implementation of HRC-systems and to drive continuous improvements of the HRC process itself, key performance indicators (KPIs) are crucial. Hence, the identification of appropriate HRC-KPIs is a critical step for decision-making and continuous improvement [5].

This paper proposes a decision-making framework for analyzing and evaluating an HRC process based on relevant safety norms and HRC KPIs. The aim of the framework is to provide a suggestion of appropriate HRC-KPIs to evaluate either an existing process or to keep in mind during the planning phase. To give special attention to process owner requirements, the tool quality function deployment (QFD) is used. Based on the application of this quality tool, it is

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possible to identify which critical HRC-KPIs shape process performance and therefore need to be measured continuously.

Nomenclature

HOQC	The House of quality for collaboration
HRC	Human-Robot Collaboration
HRI	Human-Robot Interaction
IW	Importance weight
UW	User's weight
EW	HRC experts' weight
KPIs	Key performance indicators
Num_{xx}	The number of XX
SR	Score of relevance

2. State of the art

According to the ISO/TS 15066, a collaborative operation is defined as a "state in which a purposely designed robot system and an operator work within a collaborative workspace" [6]. The collaborative space is the space in which humans and cobots perform tasks concurrently. Four collaborative operation methods are relevant for collaborative systems: safety-rated monitored stop, hand guiding, speed and separation monitoring, or power and force limiting [3], [7]. Humans and robot systems work in the same collaboration space, and the risk of collision is accepted [3]. Safety-related functions and risk assessments are critical for collaborative systems. [6,7]

KPIs are used by the management with the long-term goal of improving the company's performance by comparing the KPIs of the production system over a set time period [5]. Not only do production efficiency and cost reduction goals have to be considered, but new HRC-specific factors such as safety and ergonomics have to be included [1,5].

Papers, which classify HRC-KPIs include Coronado et al. (2020), who suggest a classification into performance and human-centered indicators, which include user experience and accessibility requirements [1]. Caiazzo et al. (2023) present a literature review of HRC-KPIs and categorize them into productive aspects, economic aspects, safety aspects, and ergonomic aspects [5].

An approach to evaluate the quality and efficiency of HRC during the planning stage using an HRC quality index is proposed by Kokotinis et al. (2023) [9]. Colim et al. (2020) specifically assess ergonomic situations in HRC-systems using primarily interviews [4]. Another paper by Gervasi et al. (2020) suggest using a different assessment framework for each KPI-category [10].

In order to execute performance management, quality tools provide an efficient approach. Quality Function Deployment (QFD) is a planning tool to identify the critical areas at the start of the design phase. Conventionally, it is used to incorporate customer requirements into the product design. Benefits of QFD include efficient communication and alignment of goals for stakeholders such as process owners, product managers and factory workers [11]. Conventional quality tools have been suggested for the use of evaluation for HRC-systems [11,12]. Bonini et al. (2019) use QFD to define requirements for an human robot interaction (HRI)-system and allocate functions to human and robot at the design phase of a production line [13]. Dhumras et al. (2023) as well use an enhanced QFD for the evaluation of robotic machine assembly design [12].

As Figure 1 shows, current research in the literature provides an overview and classification of potential HRC-KPIs, but no assessment framework [6]. Existing works that implement an assessment framework can only be used to evaluate existing HRC systems and not during the design and planning phase of the production line. Often the focus of the assessment is limited to one category [4]. There is also a lack of systematic approaches that extend the assessment of HRC-KPIs with prioritization and graphical presentation for communication. Re-evaluation and the continuous improvement process is neglected. No work provides a ranking of HRC-KPIs.

This paper aims to close this research gap by providing a framework to evaluate and rank potential HRC-KPIs. These HRC-KPIs are based on but not limited to existing works of Coronado et al. (2020) and Caiazzo et al. (2023) [1,5]. The aim of this paper is to answer the following research question:

- *How do I, as a process owner, identify the right HRC-KPIs to measure my (future) HRC task at hand to initiate a continuous improvement of the process?*

Literature	Systematic approach			Target use of method		Categories include							
Legend: ● - considered ◐ - partially ○ - not	Assessment framework	Priorisation of HRC KPIs	Extensive depiction	Design of production line	Existing implementation	Safety	Ergonomics	Efficiency	Sustainability	Technical System Requirements	Human Knowledge	Machine-related	Process-related
Coronado et al. (2020)	○	○	○	○	○	●	●	●	○	◐	○	◐	○
Caiazzo et al. (2023)	○	○	○	○	○	●	●	●	○	○	◐	◐	○
Bonini et al. (2019)	○	○	●	●	○	○	○	○	○	○	○	○	○
Colim et al. (2020)	●	○	○	○	●	●	○	○	○	○	○	○	○
Gervasi et al. (2020)	●	○	○	○	◐	◐	◐	○	○	◐	◐	○	○
Kokitanis et al. (2020)	●	○	○	●	○	●	●	●	○	○	●	●	○
Dhumras et al. (2023)	●	○	○	●	○	○	○	○	○	●	○	●	●

Figure 1 Overview of relevant research for the evaluation of HRC-KPIs

3. Approach

3.1. Framework of HOQC

This section outlines the requirements and importance of process optimization and highlights key performance indicators (KPIs) used to measure optimization from the HRC perspective. It also discusses the relationships between HRC-KPIs, whether they are contradictory or mutually reinforcing, and identifies the areas where the requirement with HRC-KPIs relationships are reflected. Finally, the results of a row of weighted calculations provide the most direct mapping of the KPIs. Figure 2 is an overview of HOQC.

Figure illustrates the complete framework of the methodology, which is defined as HOQC (House of quality for collaboration). The HOQC consists of 6 components, namely:

1) The optimization requirements (Left wall)
2) Importance weights of requirements (Column)
3) HRC-KPIs (Lintel)
4) The interaction between HRC-KPIs (Roof)
5) Process specific degree of relevance (Room)
6) Score of relevance & Ranking (Foundations)

The roles and functions of each section will be extensively discussed in the following chapters.

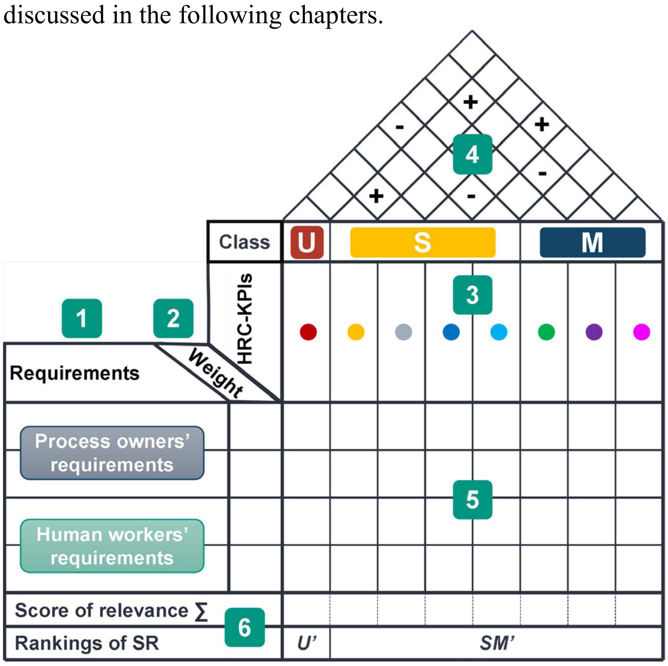


Figure 2 Overview on the structure of the house of quality for collaboration

3.2. The optimization requirements and weights of requirements

The requirements aim to represent two process related perspectives, namely, the process owners' requirements and the workers' requirements. These requirements may overlap in reality.

3.2.1. The optimization requirements

I. Process owners' requirements

These requirements are based on interviews with the process owner and typically focus on performance. Examples include basic process requirements, such as decreased labor costs, higher quality and less defects and improved production efficiency. Other requirements may include increased flexibility, and sustainability.

II. Human Worker's requirements

Human centralization is one of the most advantageous features of human robot collaboration[14]. HRC is particularly relevant in scenarios with potential to improve the ergonomics of human workers. These requirements are based on interviews conducted with the workers using the stations where HRC was or will be implemented, depending on the analysis or planning phase of the production line. Examples for these requirements are improvement of ergonomics, increasing the level of acceptance, reducing mental and physical workload, enhancing user experience[15].

3.2.2. The weights of requirements

All requirements of both perspectives are assigned weights to express their importance. The value of the importance weight (*IW*) ranges from 1 to 10, with 1 being the least important and 10 the most important. User's weight (*UW*) can be exemplarily based on Analytic Hierarchy Process (AHP) [16] or Kano analysis [17].

In addition, HRC experts' weight (*EW*) are introduced in the HOQC. Each *IW* is derived from an average of both *UW* and *EW*. Num_{Re} represents the number of both requirements offered by process owners and workers, following is the set corresponding *IW*:

$$iw_k = (uw_k + ew_k)/2$$

$$IW = \{iw_1, iw_2, \dots, iw_{Num_{Re}}\}\,;\quad iw_k \in [1,10]$$

3.3. HRC-KPIs

As described in chapter 2, KPIs are crucial for a continuous improvement process. Hence, to evaluate HRC-systems, it is hence necessary to analyze the HRC-KPIs according to the previously defined optimization requirements.

3.3.1. HRC-KPIs classification

The framework divides the set "HRC-KPIs" into three categorial elements in preparation for the subsequent evaluation:

$$HRC - KPIs = \{U, S, M\}$$

- ***U***: Uncompromisable HRC-KPIs

U contains the essential, non-negotiable factors for implemented HRC-systems. This KPI category primarily consists of safety-related indicators according to ISO criteria, as safety is the most critical aspect of HRC-systems. An HRC-system, which allows harm of a human worker is unacceptable.

- ***S***: Significant HRC-KPIs

S contains all further HRC-KPIs that don't fall into the previous category. These KPIs are generally not required in each situation, which can often represent different HRC characteristics from human, robot and collaborative aspects.

Compared to the other two categories, S is the most affluent and therefore the primary focus of the HRC-KPI analysis.

- ***M***: Significant Manufacturing-KPIs

M is frequently utilized in the analysis of production systems.It represents the most intuitively highlighted manifestations of product and process quality. These KPIs are also tailored to fit the specific characteristics of HRC scenarios for better assessment.

The elements of the set HRC-KPIS are calculated as follows: $Num_{KPIs} = Num_U + Num_S + Num_M$.

Subclass	Indicator	Class
Mechanical Safety	Collision Strength	●
	Torque	●
	Human-Machine Distance	●
	Minimum Safe Distance of Protective Devices	●
	Minimum Safe Distance with Clearance	●
Electrical Safety	Power	●
	Temperature	●
	Speed	●
	Other	●
System Safety	Risk Assessment Capability	●
	Stopping Ability	●
Safety Costs	cost of risk assessment	●
	cost for functional safety components	●
	cost of annual recertification	●
	cost for functional safety components	●
	cost for additional risk and safety assessments	●

Subclass	Indicator	Class
Time properties	Total Cycle Time	●
	Throughput	●
	Changeover Time	●
Production properties	Capacity Utilization	●
	Yield	●
	Number of defects	●
Machine Properties	Availability	●
	Overall Equipment Effectiveness	●
Energy Sustainability	Combined Production Energy Consumption	●
Material Sustainability	Product Lifespan and Quality	●
	Proportion and Numerical Value in Circular Economy Manufacturing	●
	Waste Reduction Rate and Reduction Amount	●
	Proportion & Value in Circular Economy Manufacturing	●
Digital Collaboration Capability and Adaptability	Digital Collaboration Production Ratio	●
	Human's Digital Work Capability	●
	Robot's Digitalization Level	●

Subclass	Indicator	Class
Human Biomechanical Limitations	Pressure Thresholds for Various Body Parts	●
	Elasticity Coefficients for Various Body Parts	●
	Human-Machine Force Transmission	●
Performance Requirements	Control System Performance	●
Motion Limitation Requirements	Safety Protection Space and Restricted Space	●
	Dynamic Restrictions	●
Personal Skill	Recent Job Performance	●
	Work Experience	●
	Feedback Reception and Processing Ability	●
	Communication and Collaboration Skills	●

Subclass	Indicator	Class
HRC Production Efficiency	Human Work Efficiency	●
	Human-Machine Interaction Efficiency	●
	Robot Production Efficiency	●
HRC Economic Cost	Collaboration Cost	●
	Personnel Cost	●
	Robot Cost	●
HRC Time Efficiency	Overall Motion Time	●
	Human-Machine Interaction Work	●
	HRC Cycle Time	●
Education	Education Degree	●
	Latest Training	●

Class	Description	Category	Class	Description	Category
●	HRC Safety	U	●	Technical System Requirements	S
●	Process related	M	●	HRC Efficiency	
●	Machine related		●	Human Knowledge	
●	Sustainability		●	Ergonome	

Figure 3 A taxonomy of Key Performance Indicators (KPIs) for evaluating Human-Robot Collaboration, encompassing safety, efficiency, and sustainability metrics across multiple operational dimensions

3.3.2. Categorical Integration of HRC-KPIs in HOQC

Referring to existing literature [6], [18], [19] and the 3.3.1 classification introduced, existing KPIs were collected, screened, and merged. The categorization of HRC-KPIs is necessary due to their complexity and abundance. This can be achieved by organizing them into different levels of hierarchy. The aggregation and selection of appropriate and universal HRC-KPIs in HOQC is also one of the major focus in this paper.

In Figure 3, HRC-KPIs are grouped in 8 classes and 18 subclasses. For better visualization, they are grouped in different colors for selection. Considering the efficiency and large amount of HRC-KPIs of the QFD process, it is suggested to firstly analyze the subclasses instead of every single HRC-KPI in HOQC. The interactions between HRC-KPIs 4) in Figure 2 are generally consistent, and the specific relationship can be observed in Figure 6.

3.4. Evaluating process-specific relevance of HRC-KPIs

In the HOQC, each requirement has a different degree of relationship with each of the HRC-KPIs. The final weighted relevance calculation ranks which KPIs need to be collected and analyzed in a current process or need to be focused on in a HRC design and implementation.

3.4.1. Degree of Relevance in HOQC

The KPIs are divided into the following categories, considering the importance of preventing and detecting safety hazards.

Since all elements in U are necessary for the implementation of HRC, we need to identify if any requirement violates uncompromisable HRC-KPIs in Table 1.

It shall be noted that measuring relevance in terms of specific scores is not necessary for *U* because respective KPIs need to be evaluated in any case to ensure a safe work environment.

Table 1: Degree of relevance for uncompromisable HRC-KPIs

Category	Description	Symbol in HOQC	Score
U	Necessary	√	1
	Unnecessary	×	0

S and *M* are evaluated for relevance using specific scores. The higher the score, the more relevant the HRC-KPI will be to these requirements. To clarify the degree of relevance, different symbols and values are evaluated to visualize/evaluate the different *Dr* (Degree of relevance), given in Table 2.

Table 2: Degree of relevance for significant manufacturing & HRC - KPIs

Categories	Description	Symbol in HOQC	Score
	Critically relevant	☆	10
S	Highly relevant	●	7
M	Moderately relevant	○	4
	Marginally relevant	▽	1

3.4.2. Identification of specific focused HRC-KPIs using the HOQC

The evaluation regarding process-specific HRC-KPIs is essentially one matrix $(Num_{KPIs} * Num_{Re})$ calculation with weighting and then sorting by value. In fact, it consists of three sub-matrices: $(Num_S * Num_{Re})$, $(Num_S * Num_{Re})$, $(Num_S * Num_{Re})$.

$DrU_{ij} \in \{0,1\}$, DrS_{ij}, $DrM_{ij} \in \{1,4,7,10\}$ represent the score values of the elements in their respective matrices. $(i \in Num_{U/S/M}, j \in Num_{Re})$. Figure 4 explains the calculation of the HOQC. After this calculation, the scores of relevance can be sorted by value to create a ranking of the KPIs. The highest value has the most relevance, representing the result of the HOQC.

The set *SR* (Score of relevance) at the bottom of the *HOQC* is a weighted calculation of a column with process specific relevance.

$$SR = \{sr_1, sr_2, \dots, sr_{Num_{KPIs}}\}$$

The calculation of *U* must be discussed separately from the sets *S* and *M,* but the following arithmetic logic is presented below:

$$sr_i = \sum_{j=1}^{Num_{Re}} IW_i * Dr_{ij}\ ;\ sr_i \in SR\ ;\ Dr_{ij} \in DrU_{ij} \cup DrS_{ij} \cup DrM_{ij}$$

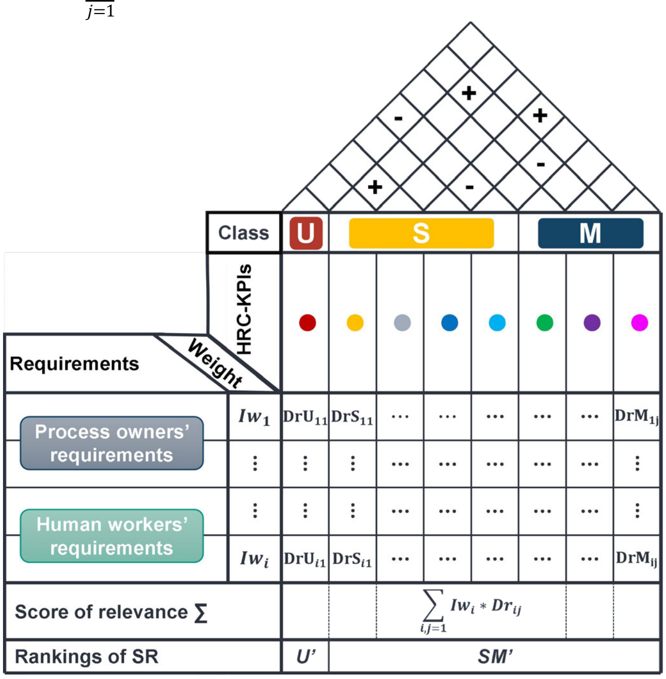


Figure 4 The process of focused HRC-KPIs Calculation

The U-set's specificity sorts only its outcomes to ascertain the shared significance of the Uncompromisable HRC-KPIs.

$$U' = \{sr'_{u_1}, sr'_{u_2}, \dots, sr'_{u_{NumU}}\}\ ;\ sr'_{u_1} > \dots > sr'_{u_{NumU}}$$

The HRC-KPIs in the sets *S* and *M* should be identified in an identical manner, because all of HRC-KPIs from both are considered significant rather than entirely uncompromisable in HOQC. Afterwards, arranging SM' in descending to obtain the set SK'_{top5}.

$$SM' = \{sr'_{sk_1}, \dots, sr'_{sk_{NumS+NumK}}\}\ ;\ sr'_{sk_1} > \dots > sr'_{sk_{NumS+NumM}}$$

$$SM'_{top5} = \{sr'_{sk_1}, \dots, sr'_{sk_5}\}$$

The HOQC output is: a new set *"Focused HRC-KPIs"* can be accessed by sorting sr_i according to value ranking as follows:

$$Focused\ HRC - KPIs = \{U', SM'_{top5}\}$$

"*Focused HRC-KPIs*" is the final result of the presented approach, which means the focused HRC-KPIs we found based on the potential process optimization requirements and their weights that are according to reasonable calculation, ranking, and filtering.

4. Exemplary Application of HOQC

HRC is widely suggested for assembly or disassembly tasks of computer motherboards [20-22]. The exemplary application is based on a process from an Automation company based in Guangdong, China. In this scenario, the production management wants to implement HRC during an assembly process for electrical control units for a computer motherboard system. Specifically, assembling computer motherboard is a complex task that involves human insertion of wire harnesses, robotic handling of the motherboard, and HRC to tighten bolts, which require different collaborative degree between humans and cobots, is the focus of this analysis. The assembly operations are as follows: Once the cobots have retrieved the motherboard, human workers will manually install all bolts in the computer chassis in sequence, pre-tightening them to 70% of the final tightening force. Furthermore, the cobots will tighten the bolts to 100% while human workers synchronize the connection of the wiring harness.

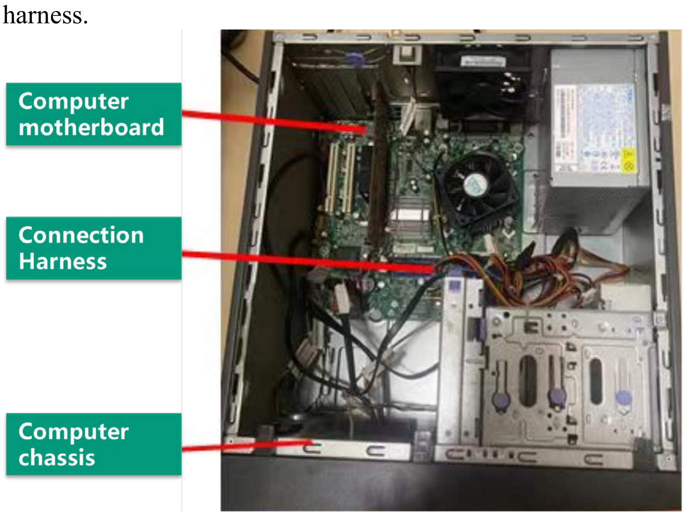
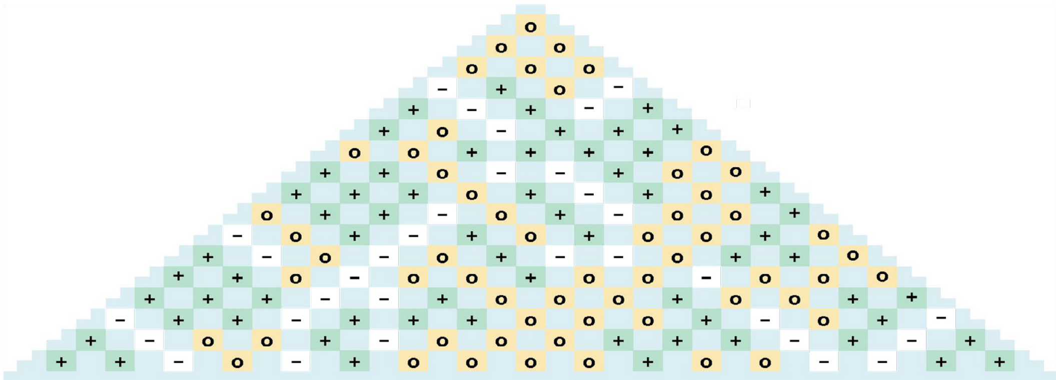


Figure 5 Target HRC scenario: Computer Motherboard Assembly



Requirements		UW	EW	Class	●				●		●	●			●	●		●			●	
				Direction	▲	▲	▲	▼	▼	▲	▲	▲	▲	▲	▼	▲	▼	▲	▼	▲	▲	▲
					U				M						S							
Types	Specific Re	UW	EW	KPIs / IW	Mecha. Safety	Electri. Safety	Sys. Safety	Safety Costs	Time Pro.	Produc. Pro.	Machine Pro.	Energy Sustain	Material Sustain	Digital Collaboration	Human Bio. Limit.	Perfor. Re	Motion Limit. Re	HRC Produc. Effi.	HRC Eco. Cost	HRC Time Effi.	Personal Skill	Education
Workers' Re	HR Distance	4	6	5	√	√	√	×	○	○				●	☆	●	☆	○	○	▽	☆	●
	HR Workspace	5	5	5	√	×	√	√	○	○	○	▽		▽	○	○	☆	●	☆	○	●	○
	Mental workload	6	9	7.5	√	√	√	√	○	○	▽	○	○	☆	●		☆	●	○	●	○	
	Physical workload	7	8	7.5	√	√	√	√	○	○	▽		●	●	☆		○	○	○	●		
	HRC Level	6	9	7.5	√	√	√	×	●	●	○	●	▽	●	☆	☆	○	●	▽	▽	●	○
Process owners' Re	Capacity / Takt	8	9	8.5	×	√	×	√	☆	☆	●	○		○	▽		○	☆	●	●	○	▽
	Production Failure Rate	8	8	8	√	×	√	√	▽	○	☆			●	▽	○	☆	▽	○	○	●	○
	Products' Qualification Rate	8	8	8	×	×	×	×		☆	▽		○	●	▽	○	○	●	○	▽	●	○
	HRC Production Ratio	6	5	5.5	√	×	√	√	●	●	▽	○		☆	●	○	▽	○	●	☆	●	○
	Cobots' cost	8	4	6	√	√	√	×	○	●	☆	▽	▽	●	●	●	○	●	☆	▽		
	Operaters' cost	6	2	4	√	×	×	×	○	○		○	○	○	●	▽	○	☆	☆	▽	●	○
	Carbon Emission Decrease	10	9	9.5	×	√	×	×		●	●	☆	☆				▽	○	○	●	▽	
Score of relevance					56.00	51.50	52.00	42.00	324.00	512.50	344.50	260.50	239.00	479.00	405.50	262.00	436.00	481.00	437.50	368.50	389.50	195.50
Rankings of SR		SK'+U'			1	3	2	4	10	1	9	12	13	3	6	11	5	2	4	8	7	14

Figure 6 Exemplary House of quality for collaboration of HRC Computer mainframe assembly production scenario

The production management uses the proposed HOQC framework when analyzing which KPIs should be more focus on during designing this assembly HRC scenario. The optimization Requirements 1) and Importance weights of requirements 2) are defined based on interviews with process owners and assembly workers and technical documentation. Because of the large number of HRC-KPIs 3) based on Figure 3, only the analysis of the Subclass is shown. The relationship between each HRC-KPIs subclass 4) and each value of *Dr* 5) is determined by HRC experts. Each score of relevance and final Ranking with *U' and SM'* 6) are calculated and generated in HOQC.

The example in Figure 6 shows as a simplified application. In HOQC, different colors are used to visualize significant results and help users quickly analyze data. For instance, blue and green represents Worker's Requirements and Process Owner's Requirements on the left side of HOQC. In terms of *SR*, red indicates HRC-KPIs in *U'* that exceed average score, while green background highlights SK'_{top5} in *Focused HRC-KPIs*.

In conclusion of the evaluation, HOQC in this scenario indicates that mechanical safety is the top sr'_{u1} in *U'* which has the most impact. Other subclasses of *Focused HRC-KPIs* should be prioritized in the following order as seen in the bottom of Figure 6:Production properties, HRC Production Efficiency, Digital Collaboration Capability and Adaptability, HRC Economic Cost and Motion Limitation Requirements. This conclusion could help production managers make a better decision for HRC implementation or optimization and ensure that the focus of this process optimization is correctly on improving the above *focused HRC-KPIs*.

5. Summary and outlook

This paper contributes to a systematic approach for the selection of appropriate HRC-KPIs based on the optimization requirements, formally considered with a QFD approach. The approach HOQC could be mainly applied to both phases of designing or optimizing one HRC process (including assembly, disassembly, etc.). On one hand, a categorial overview on HRC-KPIs was established, which provides the basis for the following evaluation. On the other hand, the house of quality for collaboration (HOQC) was developed to systematically tackle the search for essential HRC-KPIs. The strengths of the identification of appropriate HRC-KPIs for either an existing production system or during the design phase are highlighted.

As the next step, HOQC can be implemented again to screen Focused HRC-KPIs and obtain the most important indicators from Figure 3. Furthermore, after identifying a scenario's *focused HRC-KPIs* of all optimization requirements, process quality tools like quality value stream mapping (QVSM) [23] could be used to determine the goal to work towards in a continuous improvement process. Regarding future research, this paper suggests the completion of an accessible "HRC-KPIs library" to facilitate the detailed selection.

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