Evaluation and selection of workstations for an application of Human-Robot-Interaction (HRI) in manufacturing

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***Abstract*—Direct interaction between human and robot provides multiple benefits in manufacturing. In 2016, ISO/TS 15066 has been published as the first document describing safety regulation and operation modes of collaborative robots. It has motivated numerous manufacturing companies and especially SME to think about using HRI. However, a clear methodology to find the optimal combination between human's and robot's competences in various workstations is still unavailable. The main objective is to define which workstations are suitable and how they can be designed for an optimal HRI solution. This methodology takes into account the individual requirements and the future visions of the manufacturing companies starting from space and time limitations, passing by ergonomics and requirements as flexibility. The proposed methodology has been tested in various case studies within five companies.**

I. Introduction

Modern manufacturing requires flexible production lines with low running costs. Workplaces should be designed to enable the worker operating till a high age. Human robot interaction (HRI) is a fast growing technology fulfilling these requirements by complementing the benefits of humans and robots in manufacturing. [1] In [2] three main innovation drivers for HRI have been defined: 1. society, 2. industry and 3. norms and standards. [2] In the context of social impact, HRI is considered as one of the most promising solution for facing the demographical change. It is an opportunity to avoid hard physical work of workers in the production facilities which is important in industrialized nations. [3] These countries are especially affected by a growing aging. Hence, the implementation of HRI can reduce illness rates and costs for teaching or downtimes. Regarding the industrial needs as second innovation driver, companies are always seeking for new solutions to ensure flexible and cost-efficient production. On the one hand, manual workstations have high running costs and longtime process. On the other hand, a fully automated production requires high investments and engineering costs. Additionally automated solutions are usually complex, especially in assembly tasks. Consequently, HRI is an optimal approach to fill all these gaps by offering an option in between. [4] Regarding norms and standards as third innovation driver DIN EN ISO 10218-2:2011 [5] and ISO 15066:2016 [6] ensure human safety in HRI scenarios. By defining permissible collision forces and required settings of shared human robot workspaces it will help to bring HRI applications into the factories rapidly. Even if the general benefits of HRI are obvious, every manufacturing company has different needs to ensure the best performance.

This paper will present a possible approach to identify the individual best suiting workplaces for an HRI scenario. After further explanations about HRI characteristics and requirements in chapter II, the proposed approach is explained in chapter III. The case study will be presented in chapter IV. Results of the case study are presented in chapter V and discussed in chapter VI. Finally chapter VII gives an overview on the planned future research.

II. Characteristics and Requirements of HRI

As a standard for HRI [7] introduced four different levels of cooperation reaching from coexistence to direct physical interaction called collaboration, being characterized by shared tasks and shared workspace of human and robot. Every level has different requirements due to the interaction between human and robot. This distinction should ensure the suitability of HRI solutions according to the economic benefit at the facility. [7] Human safety is the most important objective in HRI and this approach offers a good solution distinguishing between necessary safety requirements. Thereby the employer only needs to pay for the necessary sensors according to the present HRI level and task type. The right balance between productivity and safety is described in [8]. In general safety can be seen as a superordinate requirement enabling the use of HRI. Because it is necessary to design a technical solution according to norms and standards it is a basic requirement. Solutions that are not considering current standards [5, 6] will not taking into account in this paper.

Manual work is cost intense and mostly applied for small numbers of pieces as it can be found in manufactories. Mass production uses fixed automation lines since it is the cheapest way to produce many equal pieces. [9] Consequently, HRI is useful in between these two extremes whenever products change during the product life cycle, quality varies or the requested unit costs are too low for complete manual work. [10] An additional factor for the introduction of robots is the cost development. Between 1990 and 2014 personnel costs were raised by 40% in Germany. In the same period the price for industrial robots dropped by 40%. [11] Since this development will continue, HRI is often introduced to transfer manual workplaces and save running costs. Thereby, companies benefit from the advantages of automation, which are "improved repeatability, increased precision and speed". [12] Due to the required flexibility in manufacturing a fully automated system often does not meet the requirements. In HRI systems the situational reactivity of the human is still present.

*Research supported by German Federal Ministry for Economic Affairs and Energy

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Fig. 1 illustrates the described zones in dependence of the production volume and the unit costs of a product. The arrows show the changes due to the innovation drivers enlarging the HRI and robot zone.

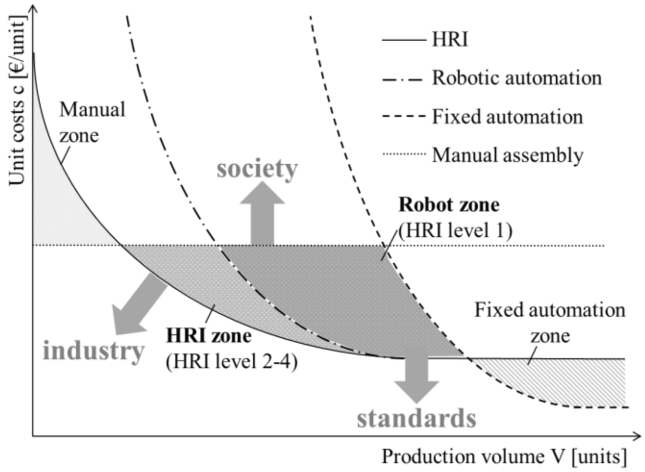


Figure 1: Effect of innovation drivers on the application of HRI (based on [9])

The HRI zone grows constantly due to fast developments in this sector. [13] Furthermore, an increasing competition in the HRI market and more providers for most of the needed components cause lower prices. Meanwhile the requirements for manual work rise due to growing ergonomic standards and conditions for the workplace design. Especially due to easy programming solutions as "learning by demonstration" less programing knowledge for the use of robots is required. Through gesture and hand guiding more SME can implement robots and HRI in plants without employing experts. [14] Consequently, HRI solutions are valuable for various industries.

To benefit best of the possibilities HRI offers it is necessary to know which abilities the involved parties possess. An overview of main advantage and disadvantage of humans and robots is given in Tab. I.

TABLE I. COMPARISON OF HUMAN AND ROBOT (BASED ON [15])

	Human	***Robot***
advantages	• Fast understanding • Mobility, tolenrance compensation • Ability of sensing • Flexible availability • Innovativeness	• Process control for constant quality • Endurance • Acceptance of unreasonable tasks • Handling of hazardous and heavy parts
dis-advantages	• Limited sensing and performance • Fatigue • High costs	• Restricted movement • Defined deployment necessary • High investment

Derived from Tab. I some activities are ideal for HRI as handling tasks where human operators can fix the part flexible and robots can handle heavy parts precisely. Thereby, human safety always has to be ensured and the operator needs legal security about his doing. [16]

Additionally it is important to ensure the acceptance of HRI systems by the employees to avoid manipulation. Therefore [1] identified six main criteria to be considered in the workplace design:

- Movement speeds and speed profiles of the robot - distances between human and robot
- Robot noises as disturbance source and as orientation source to avoid collisions
- Visual indicating systems for current and future states
- Working height of the tool center point (TCP)
- Trajectory of the robot
- Design of the robot (color, shape, material)

All criteria have confirmed influence on the workers' welfare and HRI acceptance. [17]

Furthermore, it is necessary to push the technology readiness level (TRL) of HRI to ensure industrial usage. Therefore, substantial effort is needed to speed up the development. In most cases this cannot be paid or done by a single company. In [11] the development in information and communication technologies (ICT) is analyzed during the last decades. It is assumed that the industrial use of interactive technologies is entering new fields of application. The development is basically driven by consumer products as smartphones including location sensing (GPS), fast processors and real time wireless networks. Due to the high level of acceptance many workers require these technologies in their working environment. Therefore, fast developments of safe and reliable technologies for the factories of the future are expected. [13, 18] Another important aspect for the implementation of HRI technologies is the efficiency. It has been proved with different experiments that the cycle time for processes improved significantly by using direct physical interaction between human and robot compared to manual work. [19] Other experiments showed that it is more efficient for the interaction to use longer trajectories for the robot in order to avoid collisions than to stop the movements. [20]

Nevertheless, many companies still have concerns regarding the implementation of HRI. Calculations for the return of investment are often based on unsure assumptions for improved illness rates or system reliabilities. [12] draws the conclusion that "lifting tool elimination, improved component logistics, improved ergonomics and reduced hours are the biggest improvements a large robot collaboration cell could offer, compared to manual assembly". [12] In the study only hand guided assembly was considered being a small part of the actual potential of HRI in manufacturing.

III. APPROACH / METHODOLOGY

Based on the benefits of HRI mentioned by [12] different motivations of manufacturing companies for the use of HRI were identified. On the one hand it is possible to use HRI for manual workstations since it can be healthier, cheaper and faster. On the other hand it can be used for automated workstations to make the production more reliable, flexible and space-saving.

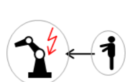
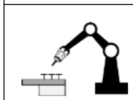
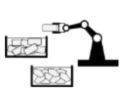
The possible motivators for an implementation of HRI in manufacturing were cut down to the different motivation targets **productivity, employee, customer, public and environment**. Each of these criteria has several dimensions shown in Tab. II.

TABLE II. CRITERIA AND DIMENSIONS OF MOTIVATORS FOR HRI

Criteria	Dimensions
Productvity (P)	• P1: flexibility • P2: reliability • P3: cost efficiency • P4: space productivity
Employees (E)	• E1: ergonomics • E2: illness rates • E3: fluctuation of employees • E4: lack of skilled labor
Customer (C)	• C1: innovation capacity • C2: required quality • C3: required documentation
Public image (Pu)	• Pu 1: attractive employer • Pu 2: light houses
Environment (En)	• En 1: improved ecobalance

As the clustering of all existing workstations is difficult in a first step the workstations with the most potential for improvements according to the motivators for an implementation of HRI were selected. According to [12, 15] and Tab. I the most useful tasks for HRI are mainly the following: handling of heavy parts, positioning of parts for higher added value by the worker, manual shut down scenarios for improved reliability, easy monotonous assembly tasks and automated logistic tasks. All mentioned workstations got a symbol for better illustration and are shortly described in Tab. III.

TABLE III. TYPES OF TYPICAL WORKSTATIONS (WS) FOR HRI

Symbol	Name and description
	*Handling of heavy parts*: robot will be used as a third hand and replace balancer systems or lifting tools – assembling tasks and quality checks can be done at the part.
	*Positioning of parts* for improved added value by the worker: the robot will hand over needed parts and the worker can hand guide the robot for precise positioning – needed at assembly lines to avoid walking
	*Manual breakdown scenario* for improved reliability – in case of an unplanned failure the system is still available via a manual emergency plan
	Easy, *monotonous assembly* tasks as screwing are shown to the robot once per produced product and afterwards the robot does the same task autonomously. In case of a product change the programming is done again
	*Automated logistic tasks*: due to high improvements in bin picking many tasks in logistics can be done by a robot. To keep the warehouse accessible for workers a HRI solution, even on a mobile platform, fits very good

Handling of heavy parts can be mostly found where balancer systems and lifting tools are provided. In many cases they are not used if possible since the handling is too slow and complicated. Robots can also replace cranes moving weights up to 300 kg. The benefit of HRI is an active handling of the parts based on gestures or preprogrammed positions.

Positioning of parts can be found whenever parts need to be brought to the main production line. By parallel work of human and robot the cycle time can be reduced and in many cases the ergonomic situation of the worker will improve since manual holding is not necessary anymore.

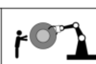
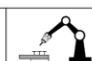
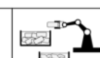
Manual breakdown scenario can be found in many automated workstations. If unplanned damages happen often or need to be prevented it is helpful to operate the workstation manually. This can be realized by hand guiding of the robot or crane. The production will slow down, but can still continue.

Easy, *monotonous assembly* can be found especially in flexible production lines since these tasks are mostly fully automated in mass production. Drilling, inserting of parts and setting connections are typical tasks. Due to solutions for easy programming no expert knowledge is necessary to realize a flexible production. [14] The benefit of HRI is a cost reduction due to few labor costs and often a psychological improvement for the worker, since monotonous work can reduce the learning ability of humans. [21]

Automated logistic tasks can be found in ware houses as well as next to the assembly lines. Since transport and packing is not adding value these activities should be reduced to a minimum. To ensure a lean material flow it can be beneficial to use order picking. [22, 23] The benefit of HRI is the accessibility of all logistic areas and saved space.

To match the individual motivation of a company for the implementation of HRI with the described typical workstations providing various benefits it is necessary to highlight connections. This is made in form of a matrix diagram dividing three levels of influences: empty field for no influence, ○ for a positive influence and ● for a strong positive influence. The matrix is shown in Tab. IV.

TABLE IV. MATRIX DIAGRAM OF CRITERIA FOR MOTIVATION AND TYPES OF WORKSTATION

Work station / Criterion					
Productivity	○	○	●	●	●
Employees	●	●		○	●
Customer	●	○		○	○
Public image	●	●		○	○
Environment	●			○	○

● **strong positive influence**

○ **positive influence**

Every criterion can be broken down into the different dimensions as presented in Tab. II. An individual evaluation of the production line is necessary in every single case. The matrix illustrates the principle of the analysis. It can be seen that *handling of heavy parts* has most potential of improvements since every criterion is influenced positively. Otherwise productivity, being according to [8] the most important criteria, for many companies can be influenced by other workstations stronger.

IV. Analysis / Case study

The presented methodology was developed by analyzing production lines in five different companies distinguishing in their size, products and production technologies. Within these companies is an automotive supplier, one of them produces gardening devices and another one agricultural vehicles. Furthermore there is one iron foundry and a producer of lavatory devices. All different companies have in common that they want to introduce HRI into their production lines. Since their motivation to implement HRI varies it was necessary to find a methodology matching their general conditions including the industrial background and the benefits of HRI. In every of the analyzed companies certain workplaces could be identified by applying the methodology in accordance to the expectations of the management. The complete process of the analyses is illustrated in Fig. 2 and described below.

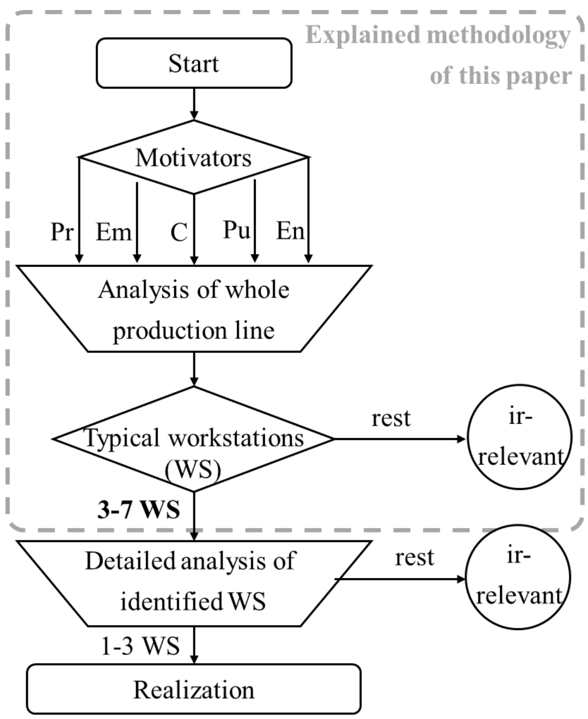


Figure 2: Flow chart of the analyses of the production line according to the HRI potential

Firstly, an intense interview took place to identify the motivation of the company split into the criteria presented in Tab. II. All dimensions of the criteria were asked separately and merged into a company specific motivation diagram with the five criteria on a scale from 0 to 1 in steps of 0.2. Based on the requirements of the company the production line got analyzed in accordance of the typical workstations for HRI presented in Tab. III and the matrix diagram shown in Tab. IV. During this process three to six workplaces within the existing production line were identified to have the most potential for HRI in accordance to the companies' background. The processes at the identified workstations were subdivided into single working steps and categorized into activities preferably done by humans and robots. On this basis, different possible layouts could be compared, the technological risk and the necessary dimensions of the robot could be evaluated and discussed. In this step, a safety company was included to ensure the safe realization of the HRI application. Mostly minor changes and requirements as designing a safe gripper were needed.

The decision between the detected HRI solutions was made differently by the companies. Some had decision making committees, some made own cost calculations based on internal decisions and some decided to build a demonstrator of the proposed technology first to reduce the risk during a long ramp-up phase.

V. Results

Based on the individual criteria of motivation to implement HRI into the production line the different dimensions of Tab. II were asked in interviews. The results only state the motivation in terms of the use of HRI and do not give an impression on the companies' strategy in terms of the asked criteria. Fig. 3 illustrates the evaluated data of the company producing agricultural vehicles as an example for the motivation diagram. Table V refers to this company as well. The five mentioned criteria are equally weighted and split into the dimensions mentioned in Tab. II. The average value of the dimensions is written below on a scale from 0 to 1 with 1 being the highest motivation.

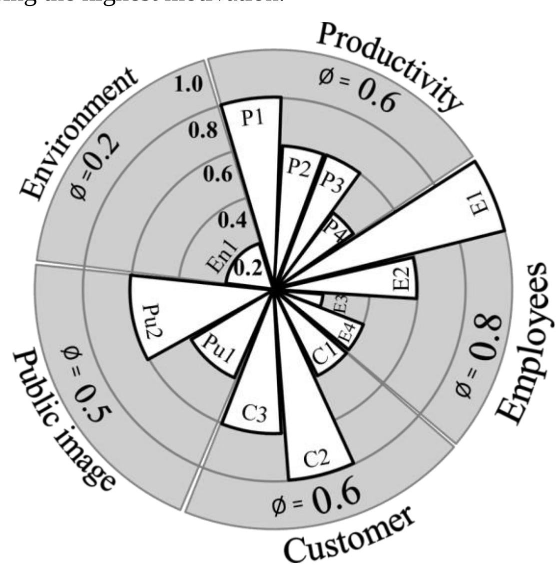


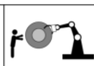
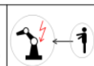
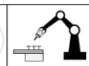
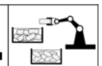
Figure 3: Example of a motivation diagram

For two of the companies the diagram got changed since they wanted to include the dimension "prevention of accidents" to the employee criteria in one case and the dimension "multiplicity of application" in another. The last dimension should give a higher ranking to the applications that could be implemented in many workstations at the plant.

All companies had the highest points on the employees or productivity criteria.

According to the flow chart in Fig. 2 at first the whole production line got analyzed on typical workstations for HRI. The numbers of identified workstations for each process step can be seen in Fig. 4. Based on Tab. IV the number could be reduced from 25 to 5 by considering the individual motivation of the company. The detailed analysis as last step was made by comparing concepts in detail.

TABLE V. EXAMPLE OF A MOTIVATION DIAGRAM

Work station / Process step					
Typical Work Stations	**5**	**7**	**6**	**3**	**2**
Productivity	○	○	●	●	●
Employees	●	●		○	●
Customer	●	○		○	○
Detailed analysis	**2**	**1**		**1**	**1**
Realization		**1**			**1**

In total seven workstations got identified for a realization in five different companies. One of them is already build at the companies' plant and another one is in the planning phase. The others are waiting for different reasons as a planned product change or other investments should be completed first. All in all the feedback of all companies was positive. This confirms the efficiency of the described method, considering their individual motivation for implementing HRI.

It is remarkable that companies, and especially SMEs, are not only looking for the cheapest solution but take their employees and customers into consideration. Especially the lack of skilled labor seems to be an important issue for implementing HRI as it was mentioned by four of five analyzed companies. They wanted to introduce HRI to reduce the complexity within one work station since complex tasks often cause failures. All analyzed companies ranked ergonomic improvements as very high.

VI. DISCUSSION

The methodology is indispensable since it identifies objective criteria for the comparison of different workstations with the possibility to implement HRI. During the case study the biggest economical effect could be raised by parallel work of human and robot eliminating waiting times. The number of cases considering five plants was too small to identify general conclusions. The studied companies already knew about HRI and possible benefits. This could have changed their perspective. Two companies already made an ergonomic evaluation of their plants. These companies had the most concrete ideas were an implementation of HRI fits best to their motivation to improve the employee criteria.

The little number of participants and the method of collecting them make the case study unrepresentative. Nevertheless, the approach is promising and should lead to further research. The benefits of clustering possible HRI applications are the easier evaluation of the possibilities and the objective criteria for a comparison. During the case study also a new cluster called *interconnection of machines by fenceless robots* was discussed. Further developments of the method are necessary due to the rising interest of companies for the use of HRI. The publication of ISO/TS 15066 [6] provides legal security for the design of workstations. Consequently, the companies need to know where the most benefits of HRI can be raised in their plant.

VII. FUTURE RESEARCH

During the development of the described methodology different unsolved topics have been detected. One of them is the general acceptance of HRI solutions. Besides the acceptance of the workers which was examined in numerus studies it is important to take other stake holders into consideration. A possible solution can be offered by the tool stakeholder-interaction-analysis (SHIA). The tool helps avoiding conflicts with interest groups inside and outside the company. By taking their interests into consideration already in the planning of a workplace their acceptance increases.

For a completely objective methodology it is necessary to also define criteria for the process steps of the detailed analysis and the realization as shown in Fig. 2. Especially the detailed evaluation of a small number of workstations should identify the benefits according to the motivation criteria in numeric benchmarks. The basis will be an assessment of ergonomics and the economic benefit of HRI. Furthermore, for other motivators as the public image and the environment benchmarks need to be developed to compare the different HRI possibilities in all dimensions. For the realization as final step of the methodology a risk assessment should be implemented. Thereby, multiple ways to implement HRI solutions are compared and the use of prototypes or demonstrators is rated. Therefore it is also necessary to consider the companies objectives. A fast implementation will be riskier than testing in advance for most cases, but according to individual conditions, as a rapid start of production, it can be helpful.

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