Enhanced service modelling for flexible demand-driven implementation of human–robot interaction in manufacturing

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Abstract: Even by providing benefits addressing the main megatrend in today's manufacturing industries human–robot interaction (HRI) lacks reasonably applied use cases, especially in small and medium-sized enterprises (SMEs). Most SMEs worry about complicated standards they have to consider when letting their employees work with a robot. Furthermore, they simply do not know where to start due to multiple promised benefits not precisely matching their requirements. Since they have individual starting points regarding their needs, available process data and documentation, it is expensive to obtain a customised evaluation of provided benefits. Thereby, the main challenge is to offer a consistent approach dealing with multiple requirements. The multi-layer concept of service modelling provides a possibility to resolve this contradiction. It aims for an overall goal by achieving predefined subgoals with individually matching methods. Thus, each manufacturing company can choose the most suitable methodology to analyse its production line. Regarding HRI it is possible to select workstations with the best fitting solution according to individual requirements. The selection will be quantified based on analyses about provided values of HRI in manufacturing. This study presents the service modelling approach for the evaluation of workstations that are best suited for the implementation of HRI in SME.

1 Introduction

Against the background of multiple megatrends, today's production is required to provide flexible and agile technologies while saving energy and resources [1]. To use the advantages of automation while keeping human operators and their flexibility in the process, human–robot interaction (HRI) is a promising and highly topical solution [2]. Nevertheless, the industrial use of HRI is still small due to a lack of overview for the multiple provided benefits, uncertainties for the difficult approval procedures and due to a shortage of experienced technology providers and integrators [3].

To increase the number of industrial HRI applications, it is necessary to demonstrate and validate the benefits of HRI according to the specific needs of different end users [4]. Therefore, a flexible solution is needed since the developments in HRI are fast and new methods and latest trends have to be considered [5]. Topics such as bin picking and hand-guided robots are developing fast due to progressions in sensor technology, and they are highly relevant for the capability of HRI systems.

The presented multi-layer approach of service modelling provides the possibility to define a meta-model with time-related process steps and adds a logical structure for conditions and relations between the classes, mostly described in the UML language. Thereby, several models can be developed to achieve a predefined overall objective with different methods. Since many companies agreed in a study by McKinsey that they would invest into automation if they obtained a valid calculation for the expected benefits [6], it seems to be an appropriate possibility to enlarge the number of industrial automation applications, i.e. increasing the number of HRI applications. The presented approach should provide the following benefits:

- Consideration of individual motivation.
- Neutral selection and evaluation of workplaces.
- The objective choice for the end user.

This paper is based on the previous work done by Fraunhofer IWU [4, 7]. It is enhanced by validated case study results, including a realised HRI application. After introducing the theory of HRI and service modelling, the methodology of the implemented layer approach is explained before presenting the case study and future research.

2 State-of-the-art

2.1 Industrial HRI applications

2.1.1 Characteristics of industrial HRI applications: HRI describes a hybrid production system where humans and robots work together without fences.

In Fig. 1, traditional production systems are displayed in white areas. While manual assembly produces a small number of individual products, it is not very cost-effective. In contrast, automated production systems represent the highest form of automation. Since general market requirements ask for individual products that are produced cost-efficiently, the demand for hybrid production systems is constantly growing. Moreover, the latest technological developments and an introduction of standards speed up the industrial use of hybrid production systems. Furthermore, the trade-off is presented between high productivity and the possibility to produce various product types, referred to as flexibility.

Market-driven factors have a significant influence on the two mentioned production systems. Manual assembly is affected by cost pressure, which prompts it to increase its productivity. The factor influencing automated systems is the increasing demand for individually customisable products, which urges it to increase its flexibility. The use of HRI offers benefits to not only productivity but also to flexibility, thus making it a viable option for existing manual assembly work stations and automatic systems.

In industrial HRI applications, different forms of interaction are distinguished that are mainly characterised by shared workspaces and shared time of a performed task [9]. Newer taxonomies even vary the tasks into shared workspace without shared task (level 1), shared task without physical interaction (level 2), shared task – handing over (level 3) and shared task with physical interaction (level 4) of human operators and industrial robots [10]. These taxonomies help define requirements and standards for different
HRI applications since they describe conditions for the set-up of robots and their performance in accordance with a human operator.

Overall the main benefits of this hybrid production include higher flexibility compared to automatic systems and lower costs than full automation [11]. Thereby, the interaction can mainly improve productivity and ergonomics since robots can perform highly repetitive and monotonous tasks – especially with high payloads [12]. Moreover, HRI can help save expensive manufacturing space and reduce downtimes due to quicker repair times [13].

2.1.2 Challenges with industrial HRI applications: Despite all mentioned benefits, industrial applications of HRI with shared workspace and shared tasks are still not widely applied in industry. The reasons are various but can be found in the uncertainty regarding safety, authorisation processes and a lack of economically useful applications [14]. Regarding safety issues, a new norm ISO/TS 15066 [15] was published in 2016. By defining maximum allowed collision forces, it expressly permits a collision between robots and human. Meanwhile, it specifies applicable limit values for a trustworthy solution. Furthermore, EN ISO 12100 describes the necessary process of risk assessment and EN ISO 13849-1 [16] sets requirements for the assessment of performance level (PL) and safety integrated Level (SIL) based on the probability of failures per working hour [17]. These requirements and standards will help deal with the authorisation procedures of needed components and will finally reduce the costs of HRI applications [18].

To manage the described challenges, it is important to develop a solution fitting the multiple and company-specific requirements. Since the initial situation varies highly according to factors such as plant size, produced batch size, ergonomic situation and level of added value, a meta-model is introduced in this paper. It provides the architecture for the process of selecting workplaces according to the individual motivation.

The implementation of HRI is especially difficult for SME. Mulligan describes: ‘In an SME, capital is typically dedicated to operations, with limited access to capital for improvements’ [19]. Therefore, it is even harder for SME to provide needed capital and knowledge and they will less likely take the risk of implementing HRI.

2.2 Approach of service modelling

Service modelling is applied whenever processes are visualised. By explaining the content and interactions of objects, it helps to understand the reactions of invisible systems. In this paper, the layered approach is visualised using the UML language.

2.2.1 Model-driven engineering: What can be done is what can be modelled [20] is one of the maxims in software development for many years. Models help structure complex problems and define an architecture to build a framework for different tasks [21]. Thereby, models can support different engineering tasks such as the communication between stakeholders and developers, verifying system designs, simplifying complex systems, and finally helping with the identification of failures [22].

By choosing cooperative approaches for challenging tasks, models can even help increase the acceptance of systems. Fischer and co-authors [23] introduced a stakeholder-driven approach for model-driven engineering to combine the naturally different perspectives from users, developers and software architects in the software development process for better understanding the needs of other stakeholders.

Describing a system by models represents a simplified existing or planned object [24]. The behaviour between systems is (sometimes stochastically) predictable and can, therefore, be described. The field of science dealing with the development of models for systems in all engineering disciplines is called Systems Engineering [25]. It uses methods of systems theory to structure, define and relate components with one another [26]. Modelling provides a possibility to split a complex system into tasks and subsystems that can be easier understood. It is possible to delegate tasks and subsystems since the purpose and the relation have been defined.

2.2.2 Service modelling: Besides the modelling of products and software, there is a rising interest in service models to describe and structure offered services for end users of production technology, especially against the background of an increasing digitalisation of production systems [27]. Modelling of software or products will not be a subject of this paper.

To keep the focus on the main requirements, the approach of modular service models was developed. It includes the following steps:

1. Collecting information.
2. Decomposition of the service into tasks.
4. Building of modules.
5. Definition of relations between modules.
6. Testing [28].

By connecting different modules of service, it is ensured that the whole service is focused on an overall goal. To address the issues of HRI correctly, a logical and a temporary structure are needed. Necessary process steps are defined first and connected, necessary data changes will be related. This can be addressed by the approach of Service Meta-Modelling and Configuration Graphs by Ulkuuniemi et al. [29] and Becker and Klingner [30].

The process management tool ARIS was established as a method of service modelling. It helps improve processes by visualising complex systems of processes within an enterprise. Empirical studies showed that companies could save time, improve customer satisfaction, increase quality and reduce costs by applying ARIS [31].

2.2.3 Model layer approach: Kern et al. [32] defined four layers (M0...M3) of modelling to relate methods (M0), models (M1) and an overall meta-model (M2) to achieve a predefined objective (M3). It is called the holistic approach to service modelling. Grandt simplified this idea and replaced Kern’s layer M3: Meta-model with the definition of an overall objective for the meta-model. This
3 Implementation of the layer approach

3.1 Definition of objectives M3

To apply the described model layer approach on a specific problem, it is first of all necessary to define the overall objective as used by Grandt in layer M3 [33]. Therefore, the boundaries of the system need to be defined. In the case of the industrial implementation of HRI in an existing production system, internal and external influences occurring on the date of the evaluation have to be considered. Internal effects cover all influences within the company. They might be caused by a changed management strategy regarding product development or by supply chain decisions. The main external effects occur in the legal standards and the latest technological developments in the field of HRI. Foreseeable changes and general trends in the internal and external effects should be considered to ensure sustainable and lasting results.

The project has to include a clear identification of the company's motivation for implementing HRI in their production line. It contains different objectives about certain company goals. Since companies have to adapt to their customer requirements and other market developments, these factors have to be considered. Finally, different objectives sum up in different significance to the overall project objective. It is characterised by a starting value as well as a value of potential improvement by the implementation of an HRI-system. The definition of the overall objective of the meta-model in layer M3 is illustrated in the UML-code in Fig. 3.

3.2 Development of the meta-model M2

Layer M2 requires the development of the meta-model in accordance with the predefined overall objective of layer M3. Since the overall objective is characterised by the user's individual 'main objective of change', it is highly dependent on the user, which has to be considered in the meta-model.

'A meta-model defines a frame and a set of rules for creating models by introducing concepts and their relationships (...). A meta-model serves as a basis for models instantiating it. Related modelling concepts usually belong to a certain meta-model.' [23]. To design the meta-model class diagrams, UML language will be used, since it uses specific semantics while being independent of platform and language. Furthermore, UML is the accepted standard modelling language for designing systems. It describes the software architecture by defining classes, attributes and methods connected by associations and compositions [34].

Necessary process steps to achieve the defined overall objective of layer M3 are defined in the meta-model. For the time-related process steps, a logical structure is added in UML, defining necessary data changes and relations. By defining relations between the UML classes, the logical structure contributes to achieving the necessary process steps.

In the case of a manufacturing company implementing HRI according to their individual requirements, it is necessary to identify and quantify the company's motivation for improving their production system. This can best be achieved after an introduction of possible benefits and main challenges of HRI systems to create a uniform understanding and to prevent disappointments. In the next step, it is necessary to identify whether the desired motivation matches the provided benefits of HRI. Thus, it is established that HRI is not the best solution for the aimed changes. If so, it is best to provide other solutions for the company, but stop the process of HRI implementation since it is a strong indicator for less successful project results.

If the motivation matches possible HRI benefits, the analysis needs to be started by picking possible workplaces for an application of HRI. Afterwards, these workplaces will be reviewed according to their potential for improvement and will be collected for consideration in the detailed analysis. Thereby, their potential for improvement will be calculated objectively and ranked in detail. Finally, the company can decide on investment while having full transparency about the resulting costs and benefits. The user decides for the best rated possible HRI workplace on a rational basis. Thus, this decision can be realised by knowing that it is the best-chosen option within the existing production line. The whole described process is illustrated in Fig. 4 with the syntax of a UML activity diagram.

Fig. 5 shows the connected logical structure of the process steps. The two parts complement each other to form the meta-model. The system's input is the motivation for improving the production system that should be addressed by implementing HRI in a manufacturing line. This motivation is stated as a request to
change. It is normally expressed unstructured and it is limited by the available investment budget of a company. Furthermore, the multiple process parameters characterising the existing production line are a given input for the system. The two inputs are marked in bold within Fig. 5.

3.3 Implementation of functional models M3

3.3.1 Identification of motivation: To achieve the company's individual objective, it is initially necessary to structure and quantify their motivation. During the general introduction of chances and risks of HRI, it is important to involve the management and all related departments of potential users of HRI. In the next step, the motivation needs to be structured and quantified to obtain a basis for assessing suitable workplaces. Due to a very diverse motivation of different companies for the implementation of HRI, it is important to identify the individual needs and requirements of a certain user. During the assessment of workstations, the fulfilment of quantified motivation criteria will help with individual evaluation.

3.3.2 Plant screening and analysis of production: Since the methodology is especially aimed for brownfield applications, the given process parameters will influence the selection of possible workplaces significantly. The Pareto-principle states that 20% of the roots cause 80% of the effects. It is assumed that this principle can also be applied to the effects of improvements and the number of workplaces. Therefore, the most important issue is the selection of the right workplaces for possible improvements. This selection can be carried out by defining certain indicator events, e.g. bad ergonomic situations or certain monotonous tasks. This might be a good starting point for improvements, since analyses had been carried out on the most beneficial HRI tasks. HRI had been implemented successfully in handling and screwing tasks, indicating a possible robot task when the work was still done manually.

3.3.3 Analysis of selected workplaces: A workplace will be selected as soon as it fulfils the requirements defined in models of M1. As soon as the selected workplaces are evaluated, the individual motivation criteria will be considered. Therefore, company-specific motivation influences the assessment and selection during the detailed analysis.

Different HRI variants are possible for each selected workplace. They may differ in terms of the level of cooperation, the risk of
implementation, necessary investment and the provided benefit for the production line.

The most suitable variants for each selected concept will be transferred to HRI concepts that can be compared with each other. According to the described individual motivation, one or more of the most suitable HRI concepts will be selected as chosen variants. Finally, these workplaces will be recommended for the implementation of HRI.

To subsequently design a model for this meta-model, it is essential to define necessary criteria for every step of the meta-model. The data should be measurable and comparable to ensure an objective selection by a quantitative analysis. As described by Grahn et al. [11], the main benefits of using HRI are the following:

- higher productivity,
- increased flexibility and
- relief of employees from hard work.

Each of the three dimensions can be split into several criteria that will be ranked at the beginning of the process to gather individual motivation. Every criterion can be quantified with equations, point scores, or durations of a certain process to measure the potential improvement.

**Assembly effectiveness** $W_{A}d$ is a possible criterion for efficiency. It indicates the percentage of value-adding activities in an assembly process based on the needed duration [35]. Thereby, it makes it possible to identify processes or workstations with a high potential for improvement in terms of value adding process steps. The main objective of efficiency is to have as much time as possible spent on value-adding processes instead of non-value adding tasks.

Value-adding processes (PV) are activities improving a part’s value during assembly, such as assembling activities, or mounting components to a part. All activities that are necessary for completing the part, but do not increase its value, are called non-value-adding processes (SV). Examples are transportation to another production facility, quality checks, rework or repositioning the part to continue the production process. Thus, SV covers all activities that are not directly necessary to build a product, but rather arise due to organisation purposes or because of customers’ requirements.

Assembly effectiveness is calculated by analysing durations for value adding and non-value adding processes as presented in the following equation:

$$W_{A} = \frac{\sum PV}{\sum PV + \sum SV} \times 100\%$$

(1)

The higher the amount of PV in the production process, the more effective it is. Due to the given long-term cost structure including workers, machinery and space, the effectiveness is a relatively simple and suitable opportunity to increase output. Lean manufacturing concepts such as one-piece-flow (avoidance of storage), Poka Yoke (defect prevention) and many more are focusing on assembly effectiveness as well.

**Employee criterion** (EAWS point scoring) is an important issue in Europe, especially due to the demographic change. When considering that available employees are getting older while performing industrial tasks, the ergonomic aspects become even more significant. Employers generally want to protect their workers from hard physical work to keep them healthy and satisfied during the whole period of employment. This aspect becomes even more important in the small and medium-sized enterprise (SME) due to the closer contact and lower hierarchy within the company.

One of the most relevant characteristics for the assessment of physical strain during industrial working tasks is the EAWS scoring system. Based on an assessment of necessary tasks, the physical strain mainly includes

- working heights,
- weight of moving parts
- body position,
- frequency of strain and
- duration of strain.

$$\text{EAWS} = \text{posture} + \text{forces} + \text{weight} + \text{extras}$$

(2)

By summing up scores according to the different levels of risks as shown in (2), the resulting EAWS point score for a workplace indicates whether it is ergonomically harmless, demanding, or even physically harmful. The highest category is marked in red colour on the ergonomic evaluation scheme and needs short-term improvement. This can be achieved by job rotation systems to shorten and vary the physical strain or by implementing lifting aids or other assisting systems at the workplace.

**The flexibility criterion** (short-term variant flexibility [% of average amount]) is an output performance indicator. Its reference value is the average amount of currently produced variants of a product. To evaluate the short-term variant flexibility, the maximum amount of variants that can be produced within a month using the given production structure has to be identified. It is expressed as a percentage of the reference value. This indicator shows the ratio by which the potential amount of produced product variants is higher than produced product variants on average.

Therefore, this key performance indicator is useful to describe a system’s short-term flexibility. This is especially important for SME with different customers ordering their products in batch sizes. Since batch sizes decline constantly, it is important to decrease the flexibility of given production systems. According to individual motivation, different workplaces can be compared by applying the objective assessments of relevant criteria.

3.3.4 **Choosing and realising HRI:** In the next step, different HRI variants are developed for improving relevant criteria. Thereby, different possibilities are developed regarding design and process distributions between robots and human operators. Consequently, it is possible to compare costs and benefits for different HRI concepts of selected workplaces. On this basis, it is possible to make a transparent decision for investment.

The entire described process is based on the method by Delang et al. [13] illustrated in Fig. 6. The functional model describes needed input and output for each process step and presents a possible method for each of them.

The identified motivation is illustrated in the form of a spider diagram. Meanwhile suitable workplaces are detected during an ABC analysis in the process step of plant screening. The two results will be the input for analysing the production, which is carried out in the form of a three-stage system. The best workplaces will be selected for further analyses. Thus, an effort-benefit-matrix is a good possibility to compare the needed time and costs with the possible benefit provided by an HRI system. Since it is a special challenge to evaluate social factors such as ergonomic and monetary improvement, it is possible to assess the area coverage about the spider diagram. Thereby, it is possible to take into account the individual motivation and to assess the non-monetary objectives. The best-rated workplace will be chosen to be realised.

4 **Results**

4.1 **Results of the case study**

Since available process data vary in manufacturing companies, and collection of data is costly and time-consuming, different methods were applied for every step of the model in the case study. In a first step, a list had been established, comprising possible methods fulfilling the requirements of the meta-model as well as possible factors for the application of the methods. Together with the companies, the decision was made which method would fit best into the given framework conditions of the respective company. Finally, a morphological box was created, filled with different methods for each process step, to provide an overview of different possibilities.

Since it is a main requirement of the approach to offer individual approaches according to the company’s situation, this
flexible solution was developed. The main intention was to offer every company an analysis according to their individual starting position, especially regarding accessible and shareable process data. As soon as a company had collected and analysed their process data, they could obtain a much more detailed analysis with the same effort as another company that had just recently started to examine their processes. An impression of the developed morphological box is given in Fig. 7 to illustrate the application of layer M0 for the developed models according to the meta-model.

The described methodology was tested in a case study with five different companies. During the study, more dimensions and criteria were added to the model since the motivation of the companies also included the view of their customers, their public image and environmental issues.

In the first step, an online-interview was conducted for all companies, and the results were presented and discussed during a face-to-face interview. In four cases the plant screening was performed by an ABC analysis considering the issues of red ergonomic assessment, low added value, critical quality situation, bottle-neck of production and necessary flexibility. The fifth managing director showed us his selected workplace.

During the plant screening between three to nine workplaces had been selected for further analysis in the different manufacturing companies. The analysis of the production line was carried out by taking pictures and videos, by recording cycle times for different manual and automated tasks and speaking to the workers about their ideas for improvements. The involvement of workers is especially important to increase the acceptance of developed workplaces.

Afterwards, the documented processes were analysed according to automatable process steps and useful redesign of the workplace. Since waiting times for robots are ineffective and decrease acceptance, one of the priorities was to avoid waiting times. Regarding the level of interaction, requirements had been demanded by the end users. Some just wanted to start with a coexisting solution to get their employees used to work next to a robot. Other workplaces required collaboration since the robot should replace an indoor crane by using a hand guiding system with force. The implementation risk in such a scenario will be much higher. Therefore, a discussion about the risks was suggested, involving experts of process design, integrators and end users.

Finally, the two companies decided to plan the suggested HRI concept in detail, including the simulation of processes, visualisation and risk analysis by a safety expert. For two other companies, the initial investment for realising the suggested HRI concept was too large. Since they could not calculate the financial benefits within the requested return of investment period, they decided not to introduce HRI in their production yet. Nevertheless, all companies were pleased with the results of the provided analysis since for most SME it is a rare opportunity for most SME to receive expert analysis of existing production lines.

4.2 Implementation of HRI application

In one of the participating companies, an HRI workplace could already be implemented since the company's priority was to realise quick implementation. It was important for the manager to get the workers used to work next to a fenceless heavy-duty robot. Therefore, an HRI application was implemented at the lowest level of coexistence. The company's main objective was to improve productivity with a higher output per cycle time and to relieve the workers from hard physical work. Consequently, the cycle time was reduced significantly while humans were still in the process and performed sensitive situational tasks. Since the robot took over exhausting and repetitive movements under heavy load, ergonomics was improved for the employees.

The collaboration of humans and robots has been realised by using SICK S3000 sensors. By detecting objects within an area of 190° for 4 m [36], the sensor works like a virtual fence. Three sensors are implemented to cover the ground. Additionally, two vertical sensors prevent the worker's hands from a collision with the robot due to nearby working spaces. The signal of the sensors is safely linked with the robot control to stop moving as soon as an unforeseen event happens. Robot movements are fast when moving towards humans to avoid fear. All operators received training explaining the safety system and outlining the benefits for their health to ensure the acceptance of the HRI solution. The effect of the solution was evaluated scientifically, and the results were very positive.

In summary, the end user was pleased with the results of the project, which was realised within six months. A picture of the realised HRI workplace is shown in Fig. 8.

![Fig. 6 Functional model of implementation M1](image1)

![Fig. 7 Application M0 via a morphological box](image2)
4.3 Conclusion

One of the results of the case study including very different manufacturing companies is that the enterprises normally expect analyses at approximately the same level of detail of their existing data. Of course, the evaluation should bring new findings, but a company with little documentation may not trust very detailed analyses. However, a very well recorded plant requires a more detailed analysis. Furthermore, there are variations regarding how well the companies already know the topic of HRI and how much they would like to be involved in the process of evaluation. In SME, the advantages of HRI are often hardly known despite the potential of increased flexibility. Hence, more explanations in the interviews are necessary to see all possible benefits. Nevertheless, larger companies can rather afford to employ experts as plant planners dealing with the topic of HRI in professional development.

In summary, the approach with the morphological box matches the various requirements very well since some companies precisely know their weaknesses and have well-documented processes. Others do not have a layout of their plant, are not allowed to share quality data due to confidentiality obligations with their customers or have not yet performed an ergonomic assessment of their workspaces. Using the different methods from the morphological box, it was possible to evaluate and compare the different requirements for the morphological box, and thereby, it is possible to adjust data types, formats and time according to the company’s needs. For the case study the needed period varied from six months for detecting, evaluating, designing and realising the workplace to nine months to decide that a workplace should be designed.

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Moreover, a profile of requirements for the morphological box should be developed. For now, the level of details for the analysis is the only characteristic. The companies are asked which methods they want to choose according to the available data and their suitable duration. In the future, more characteristics should be taken into account, and a profile of requirements should help the companies choose the appropriate methods. By constantly adjusting the methodology according to the end user’s requirements, this approach offers a sustained possibility for improvement. Depending on the needed data, reconfiguration only needs fewer hours.

It is necessary to know technical solutions and their challenges in detail to propose possible HRI applications. This paper did not address technical topics of reliable and authorised HRI applications due to various possibilities. The standardisation of HRI components and their connections is still an ongoing field of research. Thereby, it is very important to keep the methods updated, and especially regarding a fast-developing topic such as HRI, all latest developments need to be considered. Therefore, the model layer approach of service modelling is an excellent tool to verify the objective in every single step and it gives the opportunity to constantly update the model and the methods.

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7 References
