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A matrix-based approach to step-wise assess the safety of collaborative robots in manufacturing

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Abstract

Collaborative robots (cobots) allow for flexible manufacturing, supporting more customised product designs. Although safety is key for socio-technical human-cobot workplaces, existing safety assessment support like standards and guidelines require extensive experience and can be experienced as overwhelming. To make cobot risk assessments more accessible, especially for novices, and increase traceability from hazard to risk to mitigation, this paper presents a matrix-based approach that decomposes this daunting activity into smaller better manageable steps.

Keywords: socio-technical systems, risk management, collaborative robotic

1. Introduction

Collaborative robots (cobots) can help companies tackle challenges arising from dynamic markets, changing customer requirements, and supply chain uncertainties (Lasi et al., 2014). By enabling flexible manufacturing processes (Djuric et al., 2016; Du et al., 2022), cobots are an important enabler for customised products. In contrast to traditional industrial robots, cobots are easy to program and inherently safe (Kopp et al., 2021) due to four safety modes, described in section 2.2 (ISO 10218-2:2011). This allows for close human-robot collaboration, where humans can concentrate on creative and cognitive tasks, while the cobot takes over repetitive and tedious tasks (Djuric et al., 2016; Haddadin and Croft, 2016; Kopp et al., 2021). Like robots, cobots are multi-purpose machines that can be flexibly used for various applications (Matheson et al., 2019). This is enabled by cobots being so-called 'incomplete machines' that require application-specific end-effectors. Aside from benefits of allowing to design various end-effectors and resulting cobot systems, this also is a key issue as safety is paramount for human-robot collaboration and unsuitable end-effectors, such as knives or welding tools, can jeopardize a cobot's carefully designed safety features. To ensure safety, engineers cannot just design safe cobots but must consider the design of the entire cobot system and workplace. It is not sufficient to only design and assess the cobot manipulator but each application (Thomas et al., 2016) due to the unique combination of end-effectors, workplaces, humans and processes (Guertler et al., 2022). This is specifically important as cobot workplaces are complex socio-technical systems (Berx et al., 2022).
This causes challenges for risk management, which needs to identify hazards as sources of potential harm and assess the resulting risks as severity and probability of each harm (EN ISO 12100:2011; Guiochet et al., 2017). Subsequently, mitigation measures need to be defined following a prioritised sequence of aiming at (1) inherent safe design to eliminate, avoid, or reduce hazards, (2) safeguarding and complementary protective measures to reduce the impact of risk if elimination of a hazard is not

possible, and (3) information for use including safety training, warning signs and personal protective equipment (EN ISO 12100:2011). These issues are not trivial. Several standards address and support the safety of general machinery like EN ISO 12100:2011, industrial robots like EN ISO 10218-1:2011 and ISO 10218-2:2011, and in a preliminary state for cobots ISO/TS 15066:2016, along with different guidelines (Guertler et al., 2022; Härdtlein, 2021).

Despite providing valuable support, all require deep experience with cobots to identify, assess and mitigate risks. Especially for cobot novices, these steps from risk identification to mitigation can be perceived as complex and overwhelming. The traceability of hazard, harm, risk, and mitigation measure is also not always clear and documented, which complicates risk assessments reviews. This leads to the following research question of: *How can the cobot risk assessment be methodically supported to increase usability and traceability?*

To address this question, we apply the systems engineering strategy of decomposition: the underlying idea of this research is to decompose the big steps of risk identification, assessment and mitigation into multiple smaller steps that are easier to comprehend, execute and review. Based on a literature review, cobot risks, risk factors (i.e. causes), and mitigation measures are derived. Using a Multiple Domain Matrix (MDM), these factors are mapped onto each other, different human-robot interaction levels, and generic cobot applications. This allows for a transparent structural stepwise risk assessment process. For better usability and customisation, the MDM was implemented as Excel software demonstrator and evaluated for several university-based cobot testbeds, demonstrating its usability and benefits as well as current limitations. This is an important first step towards designing safe socio-technical cobot workplaces.

2. Cobot safety

2.1. Characteristics of a cobot compared to a robot

Industrial robots have been a key element of Industry 3.0 and mass production. Their ability to execute repeated tasks with high precision while offering more flexibility than other machinery, like CNC machines, enable time and cost-efficient manufacturing (Liu et al., 2022). As an incomplete machine, robots require specific end-effectors to execute specific applications and tasks (Weber, 2017). Given their capacity for high operation speed and often high amount of moving masses, robots are physically separated to ensure work-health and safety (Berx et al., 2022).

Traditionally, collaborative robots are seen as a particular type of industrial robot (European Commission, 2018), although recent research has attempted to broaden the definition of cobots to address the growing number of collaborative mobile and service robots (Guertler et al., 2023). In contrast to robots, cobots are designed to work alongside humans and support them specifically with tedious and repetitive tasks that still require high accuracy (Kopp et al., 2021). Typical cobot applications range from palletising, assembly and dispensing, handling and picking, finishing, machine tending, painting and coating, welding and soldering, inspection and quality control, to harvesting (Fairchild, 2021; Universal Robots, 2022). They are easier to program than industrial robots, which allows for increased flexibility (Kopp et al., 2021). The level of human-robot interaction can be differentiated into different steps. For instance, while Kopp et al. (2021) differentiate four steps that includes safety cell (i.e. no interaction), coexistence, cooperation, to full collaboration, Bauer et al. (2016) add synchronised as fifth step, while McGirr et al. (2022) provides finer steps by considering sequential and simultaneous operation Despite their differences, all these categorisations are based on the analysis of whether the domains of temporal work steps, work space, work tasks, and work pieces, are separated or shared for the human and robot. While for a cell-based robot, all domains are separated, they are shared in a collaboration. Figure 1 shows a combined categorisation.

In addition to classifying the level of interaction, Guertler et al. (2023) highlights the need for a multidimensional cobot taxonomy and suggests adding different levels of cobot autonomy (Haddadin and Croft, 2016), such as passive human-guided/programmed, active human-guided/programmed, semi-autonomous with user input, and fully autonomous.

	No interaction		Human-robot interaction				
	Cell	Separated	Synchronised	Co-existence	Cooperation sequential	Cooperation simultaneous	Collaboration
Work steps	Sequential					Simultaneous	
Workspace	Separated working spaces		shared workspace, but timely seperated	Shared workspace			
Work task	Separate tasks						Shared tasks
Work piece	different workpiece		same workpiece	different workpiece	same workpiece		

Figure 1. Different levels of human-robot interaction (Kopp et al., 2021; McGirr et al., 2022)

To enable the required safety protocols, cobots need to have at least one of four safety modes (ISO 10218-2:2011), as shown in Figure 2. In addition, their speed, payload, and joint stiffness are limited to reduce the risk of dangerous collisions (Djuric et al., 2016). However, like industrial robots, arm-based cobot manipulators are incomplete machines, which offer great application flexibility but also means end-effectors bear the risk of jeopardising inbuilt cobot safety features. Thus, the design of a safe cobot application requires considering not only the cobot but also the surrounding cobot system and cobot workplace (Figure 2, left).

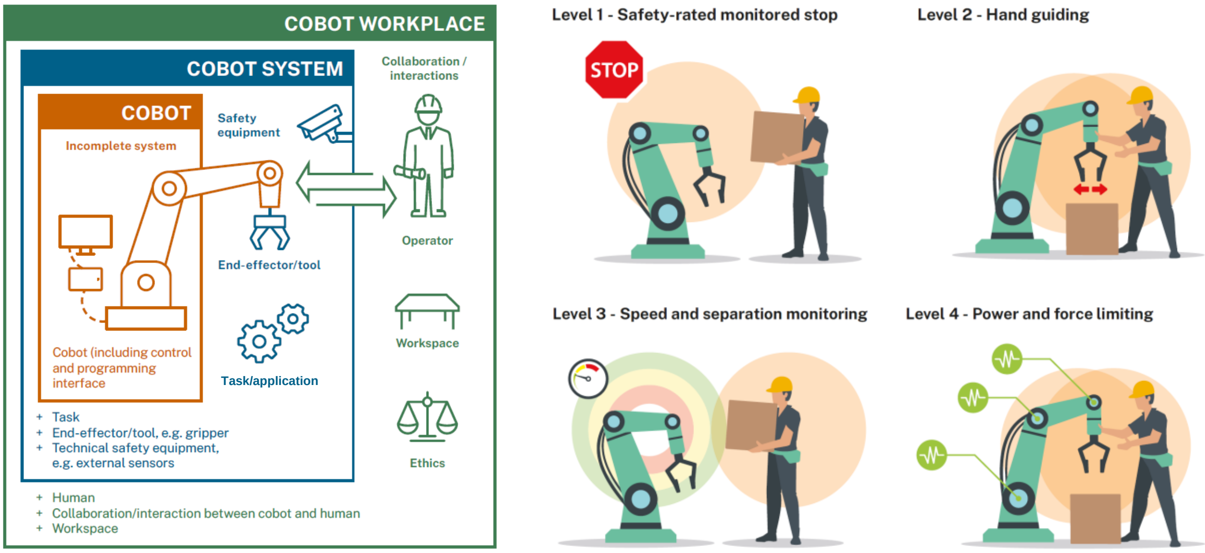

Figure 2. Left: Cobot, system, workplace; Right: Four cobot safety modes (Guertler et al., 2022; ISO 10218-2:2011)

2.2. Cobot and robot safety standards and guidelines

There are several standards addressing the risk assessment and mitigation of technical systems. The most general one is the family of " ISO 31000:2018 – Risk management", for any type of application. On a method level, the failure mode and effects analysis (FMEA) allows to identify and analyse risks in any type of product or process (Stamatis, 2003). Slightly more focussed is " EN ISO 12100:2011 – Safety of machinery", which also includes general safety design principles. Closely linked, " EN ISO 13849-1:2016 – Safety of machinery" deals with the safety of machinery control systems.

Building on these overarching standards, " EN ISO 10218-1:2011 – Robots and robotic devices" and "ISO 10218-2:2011 – Robot systems and integration" specifically address safety requirements for industrial robots and robot systems. These standards also includes collaborative applications and the four underlying safety modes (see Figure 2). " ISO/TS 15066:2016 – Robots and robotic devices" is the only ISO document with a pure focus on cobots. However, it is not a full standard but a so-called technical specification, which has not been harmonised. While it provides support for safety design and validation, it still leaves room for interpretation.

To fill this gap of an existing cobot standard, different research projects around the world have developed guidelines, such as the Fraunhofer guideline for the flexible use of cobots (Härdtlein, 2021) with generic guidance on cobot safety, and the more detailed "Guidelines for Safe Collaborative Robot Design and Implementation" promoted by the government-affiliated NSW Centre for Work Health and Safety in Australia (Guertler et al., 2022). The NSW guideline provides rather detailed support, including detailed checklists to assess cobot risks. The guideline takes into account that cobots are incomplete machines and therefore their safety is dependent on the end-effector, application, and surrounding cobot system and workplace. Still, the step from identifying risks to defining suitable mitigation measures requires experience and can be overwhelming, particularly for cobot novices.

3. Research design

This paper uses a three-step research design to identify existing robot risk assessment approaches, and develop and evaluate a new matrix-based step-wise risk assessment method. The approach uses a Multiple Domain Matrix (MDM) (Lindemann et al., 2009), combining Design Structure Matrices (DSM) to analyse dependencies between elements of one domain (Eppinger, 2012), and Multiple Domain Matrices (DMM) to analyse dependencies between elements of different domains (Danilovic and Browning, 2007). All three matrices are established complexity management methods.

(1) To obtain a comprehensive overview of robot-focussed risks and risk assessment approaches a systematic literature review is used (Levy and Ellis, 2006), and based on the established Elsevier's Scopus database (Martín-Martín et al., 2018). The search also included robots due to the often fuzzy boundaries of cobot definitions. The first three sets of search strings represent the core analysis area and focus on paper titles; the three other sets represent the context and also include abstracts and keywords. Table 1 shows the search string and exclusion criteria. In addition, an open search on Google Scholar and Google allowed to identify grey literature, such as industry reports and government guidelines.

Table 1. Scopus search string

Theme	Search string (AND connection)	Papers
Robotic	TITLE ("industr* 5.0" OR cobot* OR robot*)	272,429
Human-robot collaboration	TITLE (interact* OR collabo* OR cooper* OR "human-robot*" OR hri*)	18,814
Safety risks	TITLE (safe* OR hazard* OR risk* OR health* OR ergo*)	971
Manufacturing	TITLE-ABS-KEY (manufactur* OR produce* OR assembl* OR factory OR factories)	246
Methodical support	TITLE-ABS-KEY (measure* OR approach* OR guideline* OR method* OR design*)	194
Workplace focus	TITLE-ABS-KEY (workplace* OR "work place " OR "works space" OR workspace OR cell OR worksystem* OR applicat* OR task*)	144
Exclusion criteria	Not related to safety in manufacturing Not related to methodical safety support No full text accessible	99

(2) The matrix-based mapping started with a qualitative content analysis of the identified literature. Using an iterative coding approach based on open, axial and selective coding, adapted from grounded theory (Corbin and Strauss, 1990), papers were analysed concerning cobot and robot-related hazards, their causes, resulting harms, risks and mitigation measures. These were grouped into "risk factors", i.e. attributes that could potentially cause harm, such as payload, shape of end-effector, and workplace noise, "risks", i.e. harms such as human-robot collision, lack of trust and process inefficiency (severity and probability added in DMM analysis), and "safety measures" to mitigate risks and risk factors, which were clustered into measures related to inherent safe design, technical measures, and user information (EN ISO 12100:2011). These parameters, in combination with different levels of human-robot interaction (Figure 1), level of cobot autonomy (Haddadin and Croft, 2016), and cobot applications

(Fairchild, 2021; Universal Robots, 2022) built the basis of the MDM, shown in Figure 3. The individual DMM mappings were conducted iteratively and discussed in a team to reduce subjective bias. The risk severity and probability assessment used a structural approach, i.e. deriving them from a combination of robot/cobot type, applications and inherent tasks, and level of interaction. For better usability the MDM was implemented as an Excel demonstrator tool.

(3) The initial evaluation aimed at testing the usability, assessment plausibility and benefits of the matrix-based risk assessment demonstrator. The use cases and underlying testbeds were selected to cover a broad range of cobot applications. The focus on university-based testbeds ensured full access to the testbed, documentation and staff. Staff included researchers and technical staff, responsible for the safe design, installation, and use of the testbeds. Their feedback on the tool use and outcomes was documented and analysed to improve the tool iteratively. Noting that this focus has its limitations, the next step is applying the application of the demonstrator tool in companies.

	(1) Application + Interaction form	(2) Risk factors	(3) Risks	(4) Safety measures
input → (1) Application + Interaction form	DSM not considered for now	(1.2) What risk factors are present in a specific manufacturing process in a human-robot system?	(1.3) (= 1.2 * 2.3) What risks occur in an application (based on the risk factors)?	(1.4) (= 1.2 * 2.4) What safety measures assist an application (addressing inherent risk factors)?
(2) Risk factors	(2.1) (= 2.3 * 1.2) How much does a risk factor contribute / cause risks present in an application?	DSM not considered for now	(2.3) What risks (probability or severity) does a risk factor cause?	(2.4) How can a risk factor be addressed and thus managed by a safety measurement?
(3) Risks	DMM not considered for now	DMM not considered for now	DSM not considered for now	(3.4) (= $(2.3)^T$ * 2.4) How can risks be controlled by safety measures?
(4) Safety measures	DMM not considered for now	DMM not considered for now	DMM not considered for now	DSM not considered for now
input → (0a) Roboty type		(0a.2) How does the robot type affect the extent of a risk factor (weighting)?		
input → (0b) Lv. of autonomy		(0b.2) What weighting has the degree of autonomy of the robot onto risk factors?		

(highlighted DMMs were calculated)

Figure 3. MDM structure of the risk assessment and key question of each DMM mapping

4. A matrix-based cobot safety assessment method and tool

Figure 3 shows the MDM structure that builds the basis of the Excel demonstrator tool. The three arrows indicate key areas of user input (vector), but the tool also allows for the customisation of DMMs, such as adding or adjusting workplace-specific risk factors (vector).

DMM (1.2) maps application and interaction form onto probability, severity, and controllability of each risk factor, similar to the risk factor to risk DMM (2.3). The robot type DMM (0a.2) and autonomy DMM (0b.2) represent probability and severity weighting. Thus, different combinations of applications, interaction forms, robot types and levels of autonomy result in different risk factors and risks. DMM (2.4) maps risk factors and preventing/reducing safety measures. Risk-related safety measures (DMM 3.4) are matrix-calculated as only measures are considered that also address risk causes, i.e. risk factors. To provide further insights and guidance, the calculated DMM (1.3) lists risks for specific application and interactions forms, along with related safety measures (DMM 1.4). Considering indirect risk-dependent links, DMM (2.1) provides insights into how risk-relevant risk factors are for a specific application and interaction form.

4.1. Robot task, interaction form, level of autonomy, and robot type

The user input was realised through drop-down menus, allowing users to define the (a) specific robot task focussing on manufacturing-related tasks (Fairchild, 2021; Universal Robots, 2022), (b) the form of human-robot interaction (based on Kopp et al., 2021; McGirr et al., 2022), (c) level of autonomy (based on Haddadin and Croft, 2016), and the (d) type of robot. Explanations for each category and drop-down options are provided on separate spreadsheets. This user input is represented as an input vector for the subsequent DMM matrix multiplication. A more detailed analysis of the human, which goes beyond the level of interaction between human and cobot, is planned for the future and could include physiology, handicaps, experience with cobots, and changing attention spans.

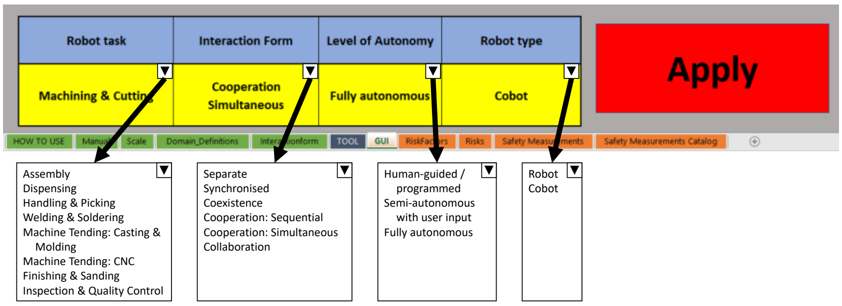

Figure 4. User input interface

4.2. Review risk factors and risks

Based on the user input, Figure 5 shows the tool output of the resulting risk factor and risk assessment (both have the same format) based on DMMs (1.2) and (2.3). These views allow users to understand how their specific cobot workplace settings favour specific risk factors and what risks are particularly relevant. In addition to technical and physical risks like collisions, risks also include psychological and social ones, such as mental strain and impact on the social environment (Tomidei et al., 2022). To support the relevance evaluation, the three factors are displayed in two two-dimensional portfolios for better visualisation. Adapting a risk matrix approach, the portfolios allow for distinguishing six levels from neglectable and very low relevance, via low, moderate, high to very high relevance in terms of requiring user attention.

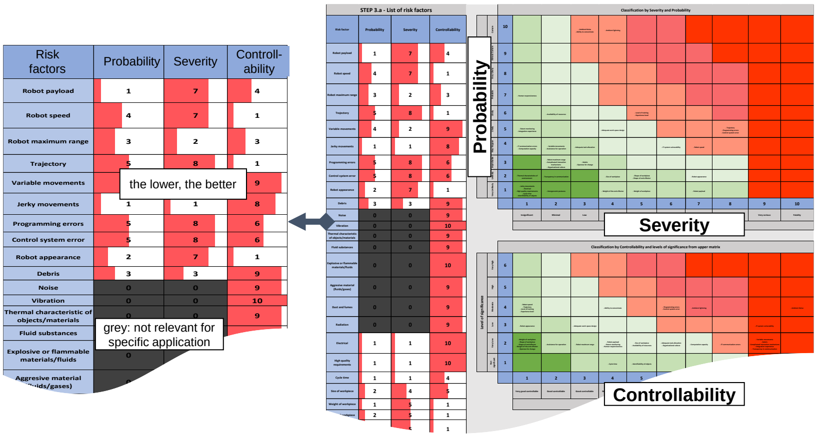

Figure 5. Risk factor evaluation view (same structure for risk evaluation)

4.3. Review safety measures

The view illustrated in Figure 6 provides the user with a weighting of different safety measures, which allows for prioritising the most effective measures for a given cobot workplace situation. Following the EN ISO 12100:2011, safety measures are grouped into measures supporting (a) inherent safe design, (b) technical measures, and (c) user information and PPE.

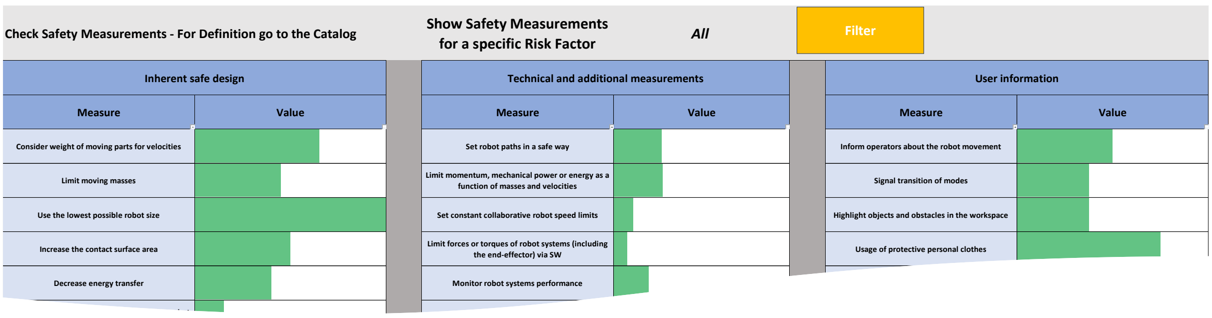

Figure 6. List of prioritised safety measures (grouped according to EN ISO 12100:2011)

4.4. Customise and add specific risk factors

Although the aim of this MDM-based approach and demonstrator tool is to provide a wide applicability, each cobot workplace situation is ultimately unique. Thus, the tool enables users to manually customise risk factors (Figure 7). Users can either ignore or increase the importance of specific risk factors, which is considered as weighting vector by the tool. An option to decrease importance was not implemented during the evaluation but was identified as an important addition.

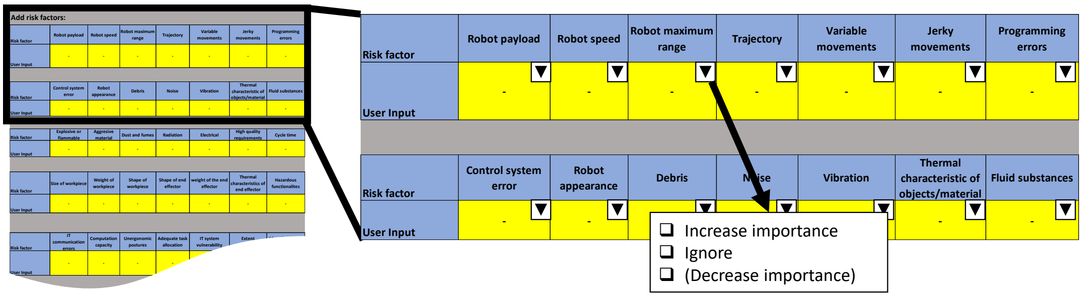

Figure 7. User interface to customise risk factors

5. Initial evaluation

The usability and performance of the matrix-based approach and tool was tested by applying and pre-evaluating using four university-based cobot workplaces. These were selected to represent a wide range of different workplace situations: (1) a cobot for handling hot steel bars moving on a conveyor belt in a steel mill: the testbed used a simplified setup with cold and shorter steel bars – the assessment was done for the testbed but already considering the future steel mill implementation; (2) a lab cobot for pick and place applications; (3) a collaborative industrial robot for manipulating and positioning heavy and bulky objects for ergonomic operator work; and (4) a soldering cobot to assist operators with high accuracy soldering tasks. The staff of each testbed was asked to join a meeting, where they could fill out the parameters of the demonstrator tool, ask questions, discuss the user interface and tool outputs, and provide feedback.

The evaluation and feedback confirmed the easy use of the tool and its help in getting a quick understanding of risk factors, risks and potential safety measures. Through its inherent checklist nature, it supported assessing aspects without the risk of neglecting key attributes.

However, the evaluation also revealed several aspects that need to be improved in future research. This includes wordings and explanations: participants stated that additional explanations would be helpful to understand specific risk factors and risks better. They also highlighted the ambiguity of "controllability", which could be changed to something like "un-controllability" to reflect that higher values are worse than lower ones. Particularly the risk factors "robot appearance" and "irritation of sensors" were recommended to be rephrased to stress that the first refers to a cobot looking dangerous, and the second refers to optical obstruction as well as lighting issues. This could also mean splitting these risk factors to address different aspects. Although the options to ignore and 'up-weighting' risk factors were seen as positive, a 'down-weighting' option was missed and should be added. To further support prioritising safety measures, participants wished to highlight mandatory legal measures in addition to the grouping according to EN ISO 12100:2011.

Discussing the resulting risk factor and risk assessments also revealed a couple of unexpected assessment values. The underlying matrix approach allowed double-checking the associated DMM mappings, which in some cases helped participants to see unobvious cause-effect relationships but also allowed to question and modify individual mappings. Although the Excel tool allowed for quick prototyping and uncomplicated use in terms of required software, it created challenges. A traceability check of mapping to investigate unexpected values was possible but time expensive as some matrix calculations needed to be split into different tabs. Participants recommended a dedicated tool, such as an online tool, which could automatically highlight relevant DMM links of a specific risk or safety measurement value and also enable tool tips to avoid the application users from switching back and forth between tabs.

6. Conclusion

This paper presents a matrix-based approach to support companies in assessing and mitigating cobot-related risks in manufacturing. Using the systems engineering strategy of decomposition, the big dauting task of a risk assessment is split into several smaller steps can help to decrease the effort and complexity of each step, make each step more easily accessible for users, and increase the traceability across steps from the identification of risks to deriving safety measures.

Thus, this paper contributes to a better understanding of cause-effect chains or networks between cobot workplace settings, risk factors, caused risks and prioritised safety measures. This helps practitioners efficiently and effectively assess and mitigate safety risks in an easily accessible and systematic way as well as engineers to design safe cobot workplaces. The approach can be applied independently to enhance organisation-specific risk assessments as well as to better understand offers and services of external companies like integrators and contractors. By considering the level of interaction between humans and cobots, the cobot's level of autonomy and technical, psychological and social hazards and risks, it goes beyond a traditionally technology-focused risk assessment. Nevertheless, the paper is just a first step towards a holistic socio-technical design of cobot workplaces. Although the evaluation was successful, it was only a pre-evaluation due to focussing on university testbeds. Aside from more applications and evaluation in general, those also need to include industry-based testbeds. As the evaluation highlighted, this would also need a more robust tool implementation moving away from Excel. While the tool's inherent checklist nature helped participants not forget relevant risk aspects, it can also be limiting as participants might not look for further aspects. This needs to be addressed in future research, along with a way to implement this into a new tool version. Both the tool and the underlying approach also need to ensure flexibility to capture the constant evolution of cobot and cobot workplace designs and new emerging risks. In addition, the matrix-based approach should be embedded into overarching cobot workplace design, including aspects like organisational change management.

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