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# Identification and classification of risk factors for human-robot collaboration from a system-wide perspective

Nicole Berx [a,b,*], Wilm Decré [a,b], Ido Morag [c], Peter Chemweno [d], Liliane Pintelon [a]

[a] Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300A, 3001 Heverlee, Belgium
[b] Core Lab ROB, Flanders Make@KU Leuven, Celestijnenlaan 300A, 3001 Heverlee, Belgium
[c] Shenkar College of Engineering and Design, School of Industrial Engineering and Management, Ramat-Gan 52526, Israel
[d] Department of Design, Production, and Management, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands

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ABSTRACT

Industry 4.0 systems in general and advanced manufacturing systems such as collaborative robots, in particular, are characterized by a high level of complexity leading to new safety concerns. Safety, specifically for collaborative robots, has been mainly addressed from a technical perspective, to safeguard the physical safety of the operator. Concerns have been raised regarding less focus in Industry 4.0 literature on how other factors, such as psychosocial can produce safety-related risks for the operator in human-robot collaboration.

This paper identifies and classifies the risk factors in a human-robot collaboration that have been described in research papers in the last decade. The resulting five classes constitute dimensions that will be used as preliminary building blocks for a safety evaluation framework to be developed in the next step. By evaluating the resulting classes with the underlying dimensions of contemporary socio-technical thinking, this paper demonstrates that these five classes offer a comprehensive, system-wide perspective including risk factors beyond technological considerations.

Topics emerging from new risks related to the impact of working with collaborative robots, such as psychosocial, ethical, and cyber risk factors will need to be taken into account in the risk factors that are important to identify, assess and mitigate before working with collaborative robots. Operator involvement and participation, especially throughout the risk assessment and mitigation cycle are recommended as new areas of attention in human-robot collaboration.

Going forward, one challenge will be the agility and adaptability of legislation to at least keep track of risk factors emerging from continuously changing technologies and to translate them into practically applicable tools for enterprises and design engineers implementing collaborative applications. Another key challenge will be the measurement of the new emerging and sometimes less technological risks.

## 1. Introduction

### 1.1. Collaborative robots as a complex, collaborative socio-technical system

Industry 4.0 is characterized by a new level of socio-technical interaction, caused by digitalization and the inter-connectedness of manufacturing resources (machinery, robots, hard- and software, etc.) and the increased organizational and technical system complexity (Kagermann et al., 2013; Kleiner et al., 2015; Pereira & Romero, 2017). This increased complexity leads to both traditional and emerging risks originating from human errors and organizational weaknesses and disruptions in complex systems (Brocal et al., 2019). The human factor is by some considered as the main link between these types of risks (Brocal et al., 2019; Komljenovic et al., 2017). Yet there seems to be a lack of methodologies and approaches to assess the influence of human factors on socio-technical systems (STS) (Morag et al., 2018; Peruzzini et al., 2020).

Collaborative robots, or cobots, are one of the enabling technologies of Industry 4.0. The main change is that cobots no longer operate in cages, but are in direct contact with the operator and that operators and cobots can perform (part of their) tasks jointly. Cobots can be considered

* Corresponding author at: Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300A, 3001 Heverlee, Belgium.
*E-mail addresses:* nicole.berx@kuleuven.be (N. Berx), wilm.decre@kuleuven.be (W. Decré), ido-ilit@013net.net (I. Morag), p.k.chemweno@utwente.nl (P. Chemweno), liliane.pintelon@kuleuven.be (L. Pintelon).

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as complex systems (Brocal et al., 2019) engendering new types of hazards (Adriaensen et al., 2019). Since a collaborative robot system combines physical and smart, networked computational elements, it can also be regarded as a cyber-physical system (Islam et al., 2019). Additionally, cobots combine human (or social) and technological aspects and in turn can be understood as a socio-technical system (Kant, 2016). Therefore, the resulting collaborative STS needs to address the human–robot interaction, covering the organizational, physical, and mental dimensions, plus the technical and cyber factors of the interaction (Kant, 2016; Peruzzini et al., 2020). Some researchers call the resulting STS a kind of human–cyber-physical system (Nardo et al., 2020; Zhou et al., 2019; Zhuge, 2011).

We situate Human-Robot Collaboration (HRC) as a contemporary development of Human-Robot Interaction (HRI), that in turn can be regarded as a particular development within the Human-Computer Interaction (HCI) research field (Huang, 2016) since robots can be regarded as a joint human–machine system (Wang & Zhang, 2017).

Several authors in the HRI field have described the different degrees of interaction between humans and robots as ranging from co-existence, over cooperation to collaboration, with a varying scope of risk factors (Hentout et al., 2019; Matheson et al., 2019; Müller et al., 2016). Mainly, the distinction between co-existence, cooperation, and collaboration, is made in function of the amount of interdependency (Bütepage & Kragic, 2017). However, as Vicentini points out, these terms have become 'buzzwords' and are in practice not consistently, and sometimes interchangeably, used (Vicentini, 2020). The major characteristics of "Collaborative" are a shared goal (Bütepage & Kragic, 2017); a shared workspace (ISO, 2020b); and concurrent task performance. The human operator and robot execute tasks together, where their respective actions can influence each other through for instance sensors and vision systems (Müller et al., 2016), and collaboration can take place in a physical or contactless way (Hentout et al., 2019). We adopt the following definitions of the International Organization for Standardization (ISO):

- The collaborative workspace is usually defined from a spatial perspective referring to the physical area in which the operator and robot collaborate to perform manufacturing tasks, in line with ISO: "collaborative workspace: space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation" (ISO, 2016, p. 2).
- A collaborative operation is defined by ISO as a "state in which a purposely designed robot system and an operator work within a collaborative workspace" (ISO, 2016, p. 1). The published draft version of the upcoming update to the ISO 10218–2 (which will incorporate safety requirements for collaborative applications that were previously the content of ISO/TS 15066:2016), furthermore defines a collaborative application as an "application that contains one or more collaborative task(s). Where the collaborative task is a portion of the robot sequence where both the robot application and operator(s) are within the same safeguarded space. Collaborative applications can include collaborative tasks and non-collaborative tasks" (ISO, 2020b, p. 6).

Interestingly, in the draft update of the ISO 10218–2, the terms 'collaborative robot' or 'collaborative operation' is explicitly not used, since only the application can be collaborative (ISO, 2020b).

### 1.2. Occupational safety and health (OSH) related to collaborative robots is raising new concerns

In this paper we will use OSH to refer to Occupational Safety and Health as defined by the European Agency for Safety and Health at Work (EU-OSHA) on their OSH-WIKI page: "Occupational Safety and Health (OSH) is an interdisciplinary activity concerned with the prevention of occupational risks inherent to each work activity" (EU-OSHA, n.d.). This definition is in line with the historic mandate of the International Labour Organization (ILO) expressed as "The protection of workers against work-related sickness, disease, and injury forms" (International Labour Organization, n.d.). Key concepts in OSH are hazard and risk:

- Hazard is, adapted from the general definitions of EU-OSHA (n.d.) and ISO (2011, 2020b), anything that can cause a personal physical injury or damage to health to any human as a result of the collaboration with a cobot.
- Risk is defined by ISO 12100 as the "combination of the probability of occurrence of harm and the severity of that harm" (ISO, 2011, p. 3).

For the objective of this paper, the strict distinction between hazard and risk as described before is not needed. When we use the term "risk factor" we understand factors or conditions that can potentially pose a risk and lead to a physical injury or damage to health for the operator or any other person in the collaborative workplace.

Recently, it has been questioned whether the impact of Industry 4.0 on OSH has been sufficiently considered (Badri et al., 2018; Leso et al., 2018; Polak-Sopinska et al., 2020). This concern is also shared by the European Agency for Safety and Health at Work (EU-OSHA): "Digitalisation, therefore, opens the door to an increase in OSH challenges, in particular of an ergonomic, organizational and psychosocial nature, that need to be better understood and managed." (Stacey et al., 2018, p. 7). And since collaborative robots are one of the defining new digitalization technologies, these new and emerging risks are also applicable for human-robot interaction (Brocal et al., 2019). Putting robots in cages or defining safety zones, is no longer sufficient when people and robots can move around freely and work together. Also, the equipment fitted on the robot (end-effector or gripper) can cause harm.

### 1.3. A need for a system-wide perspective on OSH risk factors for human-robot collaboration

When discussing safety in the collaborative workspace, this is mainly related to physical design safeguards (avoiding unintended contact and governing accessibility of the workspace) as covered extensively in the ISO 15066 (Chemweno et al., 2020; Fletcher et al., 2019). There have been several suggestions to consider other factors when designing safe collaborative workspaces to cope with the emerging risks associated with complex systems in Industry 4.0 (Chemweno et al., 2020; Polak-Sopinska et al., 2020). The need to take a broader perspective beyond technical and physical safeguards can be defended by looking at cobots from a system-wide perspective.

Systems theory and STS offer a system-wide perspective. STS is also at the basis of contemporary safety thinking and offers valuable insights into the nature of safety and accident causation (Waterson et al., 2015), although, its application to the analysis and design of sustainable, safe working environments has not been fully developed (Robertson et al., 2015). Contemporary safety approaches such as Safety-II are concerned with complex systems (Adriaensen et al., 2019). They are rooted in socio-technical thinking and provide new ways of looking at safety (Patriarca et al., 2018). An important principle of Safety-II is to focus on analyzing what goes right rather than focusing solely on what can go wrong, as is more the case in the traditional methods (labeled as "Safety-I") (Hollnagel, 2014). Safety-II also implies that it is not possible to control all aspects of work, risk will always remain. Absolute safe or unsafe systems do not exist as these systems continually evolve depending on a large set of socio-technical factors, meaning that safety is a relative concept and a continuous assessment of risk is needed (Jain et al., 2018; Kleiner et al., 2015). Safety-I and Safety-II are not mutually exclusive, but complementary, a more detailed discussion on the implications of the differences and complementarity on risk identification is not the subject of this paper.

### 1.4. Paper scope and objective

The objective of this paper is to identify risk factors (RFs) for human-robot collaboration from a broader, more comprehensive perspective than technological considerations and to classify these RFs into a limited set of classes. The research questions that need to be answered to reach the objective are the following:

- RQ1: Which factors that lead to a safety risk for the human in collaborative robotics, can be identified in recent literature?
- RQ2: "How can these RQs be grouped in a limited set of classes beyond technological considerations"?

The resulting classification is the first step towards a safety evaluation framework for safe human-robot collaboration to be developed in the next step (out of the scope of this paper). This classification proposes an answer to the need to create a comprehensive picture of what appropriate safety means in HRC, including a broad scope of safety issues that may arise (Grahn et al., 2017). Risk identification is an important step in the overall risk management process. The ISO international standard guiding risk management, defines risk identification as the first stage of the risk assessment process, followed by risk analysis and risk evaluation (ISO/IEC, 2009). This first step and the subsequent safety evaluation framework should form the basis for practical and proactive use in an industrial setting (i.e. to support risk assessment in the early stage of the design of an intended human-robot collaboration).

The main contribution of this paper is proposing a system-wide perspective for evaluating RFs in HRC that addresses the gaps identified in the literature so far. This paper identifies a broad scope of risk factors at play in a collaborative workspace and classifies these risk factors in a clear, structured, and organized way from a broad perspective. Zacharaki et al. concluded that in the past two decades, research regarding safety through hazard analysis took the smaller part of all research work conducted on safety in HRC (Zacharaki et al., 2020). The same authors also concluded that little research is available on the identification of early warnings to accidents in the context of collaborative robots (Zacharaki et al., 2020). The proposed classification attempts to fill this gap in the state-of-the-art literature.

The paper is organized as follows. In Section 2, we present the methodology used to collect and analyze the data. Section 3 presents the results of the identification and classification of risk factors in the collaborative workspace as found in recent literature. In Section 4, we analyze the results and discuss the resulting classification including its system-wide fit. Future research is discussed in Section 5. Finally, Section 6 summarizes and offers the conclusions of our investigation.

## 2. Methodology

To answer the research questions related to the objective of this paper, three main activities, each with their underlying method, have been undertaken, as visualized in Fig. 1. In this section, we discuss the methods that were applied in detail.

### 2.1. State-of-the-art literature review

As a first step in the data analysis, the sources for the risk factor identification were hypothesized and defined. This was done by performing a state-of-the-art literature review as visualized in Fig. 2. Since collaborative robots are still an emerging field, only introduced in industrial processes around 2010, this method is well suited (Dochy, 2003; Grant & Booth, 2009) and preferred to a systematic literature review. The process that was followed consisted of four steps:

Step 1: Definition of criteria

The criteria used for performing the literature review were the following:

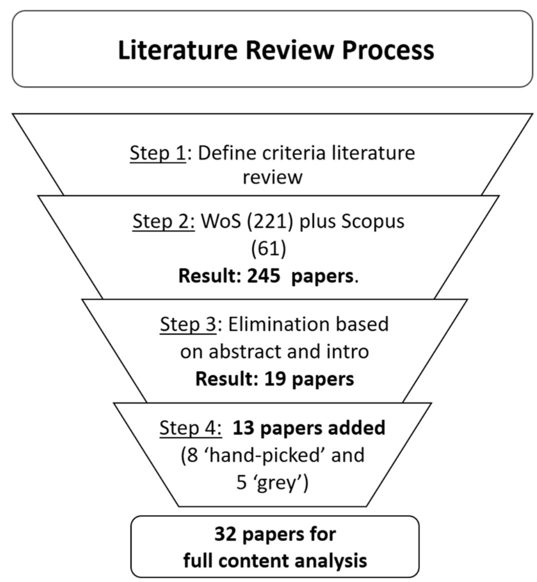


**Fig. 2.** Literature Review Process.

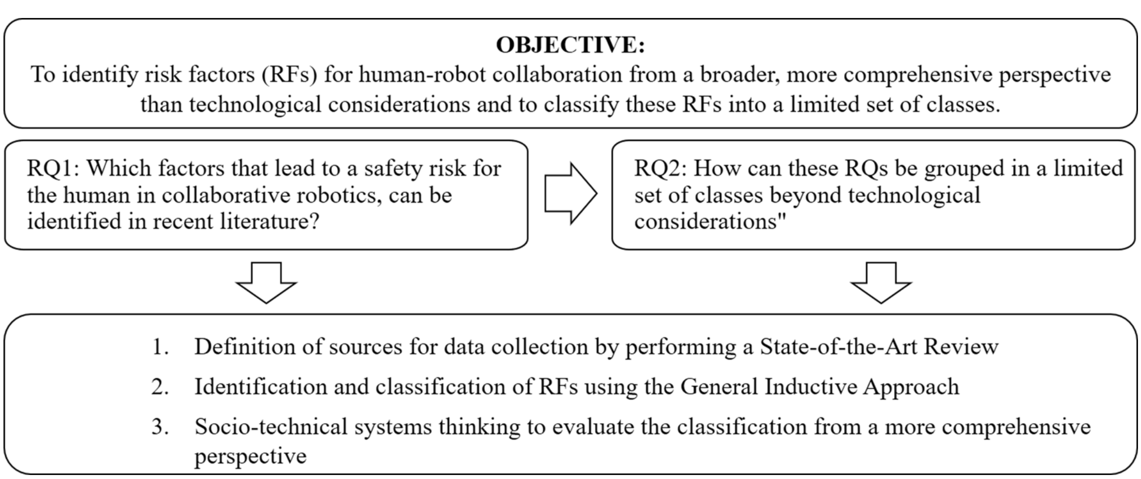


**Fig. 1.** Research activities and methodology.

 

- Scientific paper sources: the Web of Science (WoS) Core Collection and Scopus were selected as primary sources for the keyword search (see step 2).
- Limits:
  - o Timeframe: the past decade (2011 – February 2021) was taken as a timeframe. Given that this corresponds with the period that industrial collaborative robots were adopted in manufacturing and scientific research on cobots has matured only since then, this period is assumed appropriate for our objective. This time frame was verified by checking the number of publications in WoS. In the period between 2000 and 2020, 82% of all articles containing 'industrial collaborative robot' in the title were published since 2011.
  - o Language: only papers in English were selected.

Step 2: Keyword and search strings

In step 2, the initial literature search was conducted (February 18, 2021, for WoS and February 19, 2021, for Scopus) on the occurrence of the search strings in title, abstract, and keywords. The keywords and search strings were defined as follows:

- Keywords used in "quotations": collaborative robot, cobot, human-robot collaboration, HRC, Human-robot interaction, HRI, risk, hazard, safety, industrial, operator.
- Search strings were defined for both WoS and Scopus based on the keywords and excluding areas (such as agriculture or healthcare).
- After deduplication of the resulting titles (221 in WoS and 61 in Scopus), 245 titles were retained for the abstract analysis in step 3.

Step 3: Elimination after reading abstract and introduction

The final selection of papers to be fully analyzed took place in step 3. As a result, 19 papers were retained after further elimination using the following exclusion criteria:

- Too technical: papers that were predominantly discussing very specialized and detailed technical topics such as mechanical design, control synthesis or software development with no discussion on RFs for collaborative robot applications.
- Non-industrial: paper whose content was not concerned with industrial automation applications.
- Insufficiently related to scope, more specifically related to any of these topics: hazard or risk or safety for the human operator and/or human-robot collaboration.

Step 4: Adding relevant 'hand-picked' papers and 'grey' literature

In this step, some hand-picked papers and grey literature were added. The main considerations for this step were interesting literature from consultant reports the authors considered relevant for realizing the goals of this paper. Eight 'hand-picked' scientific papers were added as a result of snowballing. Finally, five 'grey' documents were added to complete the selection. This latter group concerns policy documents, issued for instance by the European Commission or EU-OSHA and industry standards (e.g. ISO). The final selection of 32 papers/documents for full review can be consulted in Appendix A.

### 2.2. Risk factor identification and classification

The resulting papers of Step 4 were analyzed based on their full text to identify the RFs for HRC as mentioned in the respective papers. To select the individual RFs from the analyzed papers, the definition of RF as described in section 1.2 was applied. The purpose of the classification is to synthesize and group the large number of individual RFs into meaningful classes and subclasses.

For qualitative content analysis, several methods can be used. For this investigation, a general inductive approach as described by Thomas (Thomas, 2006) was used. Thomas uses inductive analysis to refer to "approaches that primarily use detailed readings of raw data to derive concepts, themes, or a model through interpretations made from the raw data by an evaluator or researcher." (Thomas, 2006, p. 238). Therefore, for our purpose, the inductive approach is best suited since, as far as we know, there is no former theory for a holistic RF identification for HRC. In summary, inductive analysis was deemed appropriate, because it fits our purpose: summarizing textual data and developing the underlying structure (classification) that is evident in the raw data (Thomas, 2006).

Once the RFs were identified, the Constant Comparison method was used to classify each RF. This is an inductive approach for qualitative data analysis in which each finding and interpretation that emerges from the data is compared with already defined classes (Fram, 2015). We used this iterative process to formulate classes and subclasses to find similarities and a common denominator between the individual RFs. The RF classification was constantly revisited seeking ever more detailed classes until a reasonable number of classes was obtained. According to Thomas, 3 to 8 is an acceptable number of different categories or classes (Thomas, 2006).

The detailed process used (see Fig. 3) was the following:

- Each identified RF was registered in a spreadsheet, noting the quotation of the relevant text in the paper with accompanying source reference (author and page).
- A first class code was attributed to the first RF and consecutively to all the following. In this way, different classes and subclasses were developed. Each interpretation of RF is compared with existing findings. During the process, classes are created and abolished to finally arrive at a satisfactory number of classes and subclasses.
- This process was done three times to lead to a final set of reduced core classes and corresponding subclasses.

Two activities supported the consistency during the classification iteration cycle and proofed to be very useful to keep track of different underlying topics within subclasses. On the one hand, the type of content of each class and the corresponding subclass was labeled, briefly described, and continuously updated (see the final version in Table 2 in Section 3). Additionally, the emerging classes and subclasses were plotted and replotted in an Ishikawa diagram to visually support the classification process and underlying relationship with subclasses. An example of an intermediate version of the Ishikawa diagram is illustrated in Appendix B.

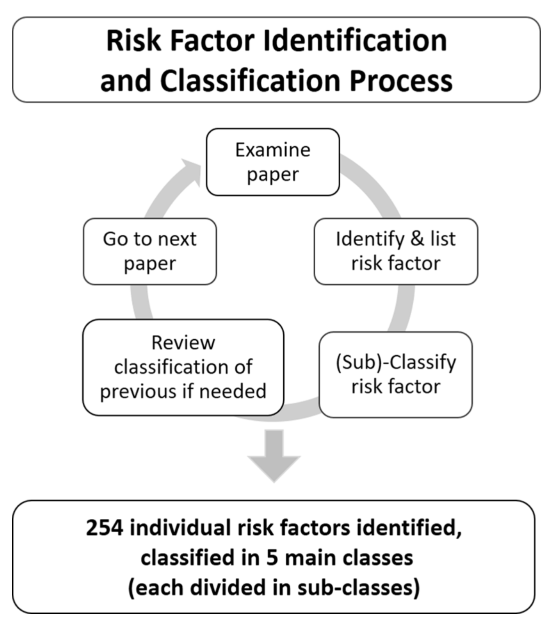


**Fig. 3.** Visualization of RF Identification and Classification Process.

**Table 1**
Socio-technical dimensions of contemporary advanced manufacturing systems.

| | Human (or Human Factors) | Organisational (incl Culture, Processes) | Social | Techno-logical | Building Infra-structure | Environ-mental | Eco-system | Year | Publication title |
|---|---|---|---|---|---|---|---|---|---|
| Baxter and Somerville | √ | √ | √ | √ | | √ | | 2011 | Socio-technical systems: From design methods to systems engineering |
| Pasmore et al. | √ | √ | √ | √ | | | √ | 2019 | Reflections: Sociotechnical Systems Design and Organization Change |
| Neumann et al. | √ | √ | √ | √ | | | | 2021 | Industry 4.0 and the human factor – A systems framework and analysis methodology for successful development |
| Klemsdal et al. | √ | √ | √ | √ | | | | 2017 | The Organization Theories of the Industrial Democracy Experiments Meet Contemporary Organizational Realities |
| Parker & Grote | √ | √ | | √ | | | | 2020 | Automation, Algorithms, and Beyond: Why Work Design Matters More Than Ever in a Digital World |
| Davis et al. | √ | √ | | √ | √ | √ | | 2014 | Advancing socio-technical systems thinking: A call for bravery |
| Davies et al. | √ | √ | | √ | | √ | | 2017 | Review of Socio-technical Considerations to Ensure Successful Implementation of Industry 4.0 |

**Table 2**
Description of classes and subclasses

| Class and subclass label | Description |
|---|---|
| 1. Human | Is understood as being related to the human operator and any other human in the vicinity of a cobot. |
| Psychosocial | RFs related to psychological and social factors. |
| Physical ergonomics | RFs related to working postures and Musculoskeletal Disorder (MSD) risk. |
| Cognitive ergonomics | RFs linked with mental processes. |
| 2. Technology | Is understood as the combination of (traditional) Information Technology, such as computers, with new digital industrial technology associated with Industry 4.0, such as robots. |
| Operating system | RFs concerning the enterprise automation system overarching the cobot system (more related to Information Technology). |
| Cobot system | RFs related to the cobot and the automation directly steering and controlling the cobot. |
| 3. Collaborative Workspace | Is understood as the physical area in which the operator and robot collaborate, cf. ISO 15066 “space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation”. |
| Physical design | RFs regarding the physical and spatial design of the workspace. |
| Maintenance | RFs concerning maintenance activities on the cobot or in the workspace. |
| 4. Enterprise | Is understood as the legal entity where the HRC takes place. |
| Organizationalergonomics | RFs related to organizational structures, policies, and processes of the enterprise (in line with the IEA definition). |
| Ethics | RFs concerning moral principles that govern the enterprise strategy and operations. |
| Safety strategy | RFs related to the high-level enterprise strategy and plan that is concerned with workers’ safety. |
| Technology strategy | RFs related to the high-level enterprise strategy and plan that is concerned with the introduction and adoption of (new) technology. |
| 5. External | RFs related to events, phenomena, or decisions taking place outside the enterprise and not under the control of the enterprise. |
| Regulatory | RFs included in regulations issued by the government (directives, laws) or any other recognized official body (ISO, EU-OSHA, ILO). |
| Environmental conditions | RFs related to conditions outside of the collaborative workspace, e.g. weather conditions. |

### *2.3. System-wide properties through the lens of STS*

We propose a socio-technical perspective to discuss the system-wide properties of the resulting classification against the driving dimension of contemporary STS.

Baxter and Sommerville defend the need to adopt a socio-technical approach, considering human, social and organizational, as well as technical factors for the design of organizational systems (Baxter & Sommerville, 2011).

New technologies and digitalization have transformed industrial processes in the past two decades and simple tasks, previously done by human operators have now been replaced by machines and technical systems (Oborski, 2003). Oborski argues that as a result, the role of the human operator has become more important and that the key success factor for advanced manufacturing is the coexistence of technology, information processing, and human factors (Oborski, 2003). The lack of attention to human factors in Industry 4.0 is also pointed out by Neumann et al. (Neumann et al., 2021). Other authors see STS design as a suitable approach for advanced manufacturing today (Klemsdal et al., 2017; Neumann et al., 2021; Pasmore et al., 2019). Some authors argue that Industry 4.0, has been too focused on the technological aspects and therefore can benefit from applying STS thinking to consider other aspects, such as social and organizational (Davies et al., 2017; Klemsdal et al., 2017). The application of STS to new technology and complex systems is not new but calls for more “bravery” according to Davis et al (Davis et al., 2014). They believe that the focus of socio-technical systems research to date has been too narrow and that it should move beyond its dominant focus on new technologies to a concern for complex systems (Davis et al., 2014).

STS theory added the ‘social’ dimension to the ‘technical’ dimension and strives for joint optimization and proper cooperation of the technical and the social system (Klemsdal et al., 2017). An important change in the contemporary application of STS is the consideration of human-centered design principles in the development, design, and procurement of new technology (Parker & Grote, 2020). The evolution in human-technology relations is according to Parker and Grote different from previous technological evolutions since humans and technology now function as a team of equals (Parker & Grote, 2020). This calls for a need for a “joint - and proactive - consideration of technology, people, and organizations to create work that is both healthy and productive.” (Parker & Grote, 2020, p. 34).

Pasmore et al. are proposing a “Socio-technical systems design for organizations of the future”, consisting of four components: ecosystem, organization, technical system, social system (Pasmore et al., 2019).

Building on the above discussion on the link between STS, Industry 4.0, and complex systems, we see three recurring building blocks for complex industrial systems: human, organizational and technological. These three dimensions are consistently mentioned by all authors as can be seen in the overview in Table 1. A dimension that is mentioned several times is 'social', we have understood this as the interaction between (groups of) people and therefore regard the 'social' dimension as part of the organizational building block (Morag & Luria, 2018). Other dimensions, such as infrastructure, environment, and ecosystem are occasionally mentioned.

Since collaborative robots can be seen as a complex system, the three STS dimensions discussed before should also be governing HRC and hence the risk factors for HRC should also reflect these three dimensions. In Section 4.3, the RF classification is discussed against these three necessary dimensions of STS.

## 3. Results

In this section, the outcome of the literature review and the resulting identification and classification are presented. The process of identifying and classifying the RFs, based on the analysis of the 32 papers/documents, resulted in a table of 254 individual identified RFs. In the list the RFs were quoted as described by the author(s)), each of them labeled with a class, subclass, and source reference (author(s), publication, page, year). Five main classes, each with at least two subclasses, resulted from the classification: (i) Human; (ii) Technology; (iii) Collaborative Workspace; (iv) Enterprise and (v) External. An overview of these classes and subclasses with a brief description is presented in Table 2.

From the 32 papers/documents analyzed, 29 contributed to the RF identification. How each paper/document contributed to the (sub) classes, is displayed in Table 3.

## 4. Analysis and discussion

In this section, the results of the investigation are analyzed, first in general (4.1), then by class and subclass (4.2). The resulting classification will be discussed and evaluated in Section 4.3.

### 4.1. Overall

The literature selection illustrates the recency of the papers and documents that were analyzed. Twenty-seven documents (84 %) were published in or after 2017.

As presented in the previous section, five classes resulted from the classification process. Five is an acceptable number to create a model incorporating the most important classes according to Thomas (Thomas, 2006). This is also a satisfactory answer to RQ2, to group the RFs in a limited number of classes.

For the deeper analysis of the classification, the number of individual RFs attributed per class and subclass was counted to represent the weight of each (sub) class. The distribution of RFs over the five classes will be discussed in more detail in 4.2

Regarding the contribution of each paper to the classification process (Table 3), we can conclude that few authors look at RFs from a more integrated and system-wide perspective. All but three analyzed papers (Koppenborg et al., 2017; Michalos et al., 2015; Neumann et al., 2021) address Technology RFs, this confirms the reigning focus on technological aspects. This focus should not surprise since these aspects will remain essential to ensure operator's safety, given the fast-changing technology and potential emerging risks in collaborative robotics. Nine papers mentioned RFs that were attributed to the Technology and Human classes and reflect the need to also include human factors in HRC. Only two papers contributed to all five RF classes. This can partly be explained by the selection of the search strings, but it also points out the lack of research on how system-wide RFs can influence the safety of humans in the collaborative workspace.

### 4.2. Detailed analysis

The details of the classification will be presented and discussed per class (in declining order of the number of identified RFs). We decided to consider each identified RF equally important and counted the RFs per (sub) class. Although there is no benchmark to evaluate the quantification of the RFs per (sub) class, the relative importance provides a basis for assessing the nature of the RFs that have been identified from recent literature and the significance of the class they were assigned to as result. In the following subsections, each class and subclass are described, and observations and interpretations on the relative importance of the (sub) classes are discussed.

#### 4.2.1. Five main classes

The class with the highest number of identified RFs is Technology with 113 RFs, representing 44% of all 254 identified RFs. This finding is in line with the earlier mentioned concern of over-attention to technical safety as reflected in the regulations and adopted standards. Yet at the same time, even more RFs could be expected, as new risks emerge as the result of technological advancements and that regulation can hardly keep track and is reactive (Badri et al., 2018).

The second highest class is Human with 68 RFs or 27 % of all total RFs. These two most important classes represent together 71% of all identified RFs. Only 3 RFs (identified from 2 papers) related to the external environment were identified and the Collaborative Workspace and Enterprise class each represent respectively 36 (or 14%) and 34 (or 13%) of all identified RFs. Within each main class, at least two subclasses were distinguished. The distribution of identified RFs per class is represented in Fig. 4. The details of the quantification of RFs per class and subclass are summarized in Appendix D. An illustration of how some RFs provided the content for the subclasses is provided in Appendix E.

#### 4.2.2. Technology

The Technology class contains the highest amount (113 or 44%) of identified RFs. Technology is understood as the combination of (traditional) information technology, such as computers, with new digital industrial technology associated with Industry 4.0, such as robots (Rüssmann et al., 2015). Initially, it was considered to separate information system and cobot system, but during the iterative process and based on discussions amongst the authors of this paper, it was decided to group both systems in the Technology class, because of their intertwinedness within the enterprise automation. The respective subclasses are described as follows:

- Cobot system (99 or 88% of identified RFs in Technology): RFs related to the cobot and the automation directly steering and controlling the cobot. Included in this subclass are RFs related to:
  - o Software: general cobot programming errors such as bugs, risks as a result of Artificial Intelligence (AI) built into the software, faulty/insufficient interface communication; AI/Machine Learning algorithm programming related issues; bugs or risk related to the integrity of the system;
  - o Control software: the programming that controls the movement, speed, and force exerted by the cobot. RFs potentially leading to collision (for instance as a result of not respecting the biomechanical limits, or insufficiently monitoring distance and speed) were classified in this subclass as the cause for these RFs does not lie with the operator but with the cobot.
  - o Hardware: risks related to physical components of the cobot (body, control system, manipulators)
  - o Tooling: RFs concerning for instance the workpiece, gripper, and end effector.
  - o Application-specific hazards: RFs (e.g. fumes, chemicals, and hot materials…) created by the specific collaborative applications (e.g. welding, assembly …).

**Table 3**
Contribution per author towards the attribution of RFs to (sub) classes.

| | | **Human** | | | **Technology** | | **Collaborative Workspace** | | **Enterprise** | | | | **External** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | year | Psychosocial factors | Physical ergonomics | Cognitive ergonomics | Operating system | Cobot system | Physical design | Maintenance | Organisational ergonomics | Ethics | Safety strategy | Technology Strategy | Regulatory | Environmental conditions |
| Matthias et al. | 2011 | | | | | √ | | | | | | | | |
| Missala | 2014 | √ | | | | √ | | | | | | | | |
| Michalos et al. | 2015 | √ | | √ | | | | | | | | | | |
| ISO 15066 | 2016 | √ | √ | √ | √ | √ | √ | | √ | | | | | |
| Steijn et al. | 2016 | | | √ | √ | √ | | √ | √ | √ | √ | √ | √ | |
| Grahn et al. | 2017 | √ | | | √ | √ | | | | | √ | | | |
| Guiochet et al. | 2017 | | | | | √ | | | | | | | | |
| Khalid et al. | 2017 | √ | √ | | | √ | √ | | √ | | | | | |
| Koppenborg et al. | 2017 | √ | | √ | | | | | | | | | | |
| Lasota et al. | 2017 | √ | | | √ | √ | | | | | | | | |
| Aaltonen, 2018 | 2018 | | | | | | | | | | | | | |
| Gopinath et al. | 2018 | √ | | √ | | √ | √ | | | | | | | |
| Jansen et al. | 2018 | √ | √ | √ | √ | √ | √ | | √ | | | | | |
| Leso et al. | 2018 | √ | | | | √ | | | | √ | | | | |
| Stacey et al. | 2018 | √ | √ | √ | √ | √ | | | √ | √ | | √ | | |
| Villani et al. | 2018 | √ | | | | √ | | | | | | | | |
| Aldini et al. | 2019 | √ | √ | | | √ | √ | | | | | | | |
| Antonelli et al. | 2019 | √ | | | √ | | | | | | | | | |
| Gopinath & Johansen | 2019 | | | | | √ | | | | | | | | |
| Hentout et al. | 2019 | √ | | | | √ | | | | | | | | √ |
| Moore & Starren | 2019 | √ | | √ | √ | √ | | | √ | √ | | √ | | √ |
| Nikolakis et al | 2019 | | | | | √ | | | | | | | | |
| Chemweno et al. | 2020 | | √ | √ | | √ | √ | | | | | | | |
| Colim, 2020 | 2020 | | | | | | | | | | | | | |
| Gervasi et al. | 2020 | | | | √ | √ | | | | √ | | | | |
| Hanna et al. | 2020 | | | | | √ | | | | | | | | |
| ISO 10218–1 | 2020 | | √ | | √ | √ | | | | | | | | |
| ISO 10218–2 | 2020 | | | | | √ | | | | | | | | |
| Kopp et al. | 2021 | | | | | √ | | | | | | | | |
| Zacharaki, 2020 | 2020 | | | | | | | | | | | | | |
| Gualtieri et al. | 2021 | √ | | | | √ | | | | | | | | |
| Neumann et al. | 2021 | √ | √ | √ | | | | | √ | | | √ | | |

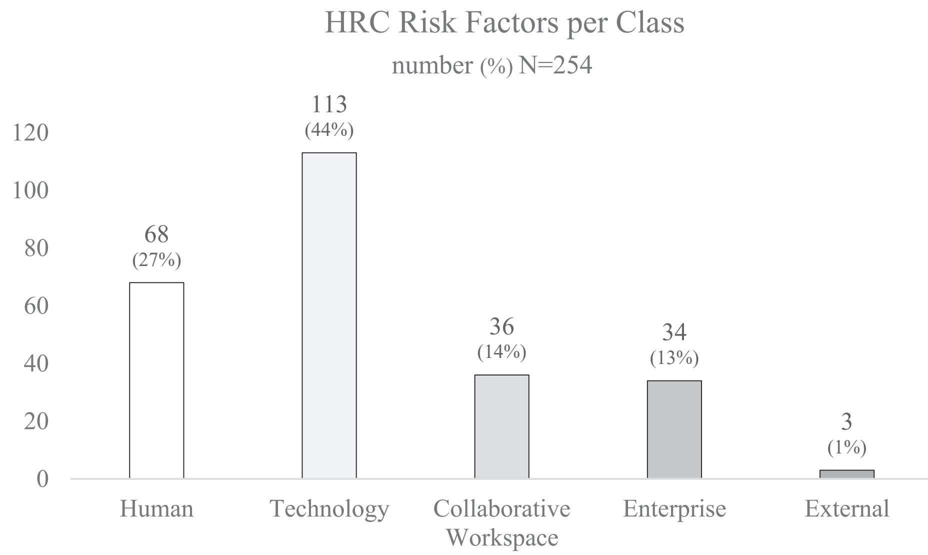


**Fig. 4.** Distribution of identified RFs per class and subclass.

- o Systems status communication: risks as a result of the unawareness of the operator of the system status, potentially resulting in an unintentional collision with the cobot.
- Operating System (14 or 12% of identified RFs in Technology): The enterprise automation system overarching the cobot system (more related to information technology). In this subclass RFs related to the following topics were included:
  - o Security: RFs related to the protection of the enterprise system, such as cybersecurity or the use of cloud data storage.
  - o Data management: RFs related to managing data as an enterprise resource. For instance due to insufficient system capacity for data computation leading to delay in the cobot's reaction.

The first observation to be made related to the identification of Technology RFs is the number of recorded RFs. This number is influenced by the more detailed granularity of the technology RFs, due to the inclusion of the draft adaptation of the ISO 10218–1 and 10218–2 standards, which provide an extensive and detailed list of risk hazards (ISO, 2020a, 2020b). The risk factors listed in parts 1 and 2 of the ISO standard 10218 were combined to avoid double counting. However, the ISO 15066 was also included, since it is a different standard.

With 88% of all RFs in the Technology class, the cobot system is the largest subclass. This reflects the increasing complexity of cobot technology but also highlights an effort predominantly aligned to a technocentric view the authors highlighted previously. The detail of the topics included (hardware, tooling, application-specific RFs) is also a reflection of the ISO standards. Risk factors related to the programming of the robot represent half of all cobot system-related RFs. Since a robot consists of two parts, the machine or arms, and the control system, it is no surprise that programming RFs related to both aspects were identified. Excluding programming errors to safeguard the integrity of the software determines to a large extent whether a robot can be used safely (Steijn et al., 2016). This applies of course not only to the cobot system but also to the operating system and was reflected in the mentioning of security and data management for the operating system as potential RFs. Regarding security, information security (for instance in cloud storage) is seen as a potential risk factor. Additionally, several authors acknowledge specifically cybersecurity as a risk factor (Gervasi et al., 2020; Jansen et al., 2018; Stacey et al., 2018; Steijn et al., 2016), which is a more recent concern voiced in Industry 4.0 literature (Mittal et al., 2018) and also included in both parts of the draft update of ISO 10218 (ISO, 2020a, 2020b).

*4.2.3. Human*

The Human class represents (68 or 27%) of all identified RFs. It groups RFs related to the human operator and any other human in the vicinity of a cobot. In this class, three subclasses were distinguished in the following order of importance based on occurrence incidences in the reviewed literature cases: psychosocial (54%), cognitive ergonomics (28%), and physical ergonomics (18%). The label Human was preferred over the term human factors, because of the ambiguity in the use of human factors in literature as sometimes it is used in a very general sense and sometimes it is explicitly referring to the definition of the International Ergonomics Association (IEA). We will look into this a bit deeper in the following paragraph as it is related to the understanding of the subclasses used within Human.

The IEA, defines Human Factors on their website as follows: "Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design to optimize human well-being and overall system performance." (The International Ergonomics Association, n.d.). The IEA further mentions three underlying concepts within the discipline of Human Factors: physical ergonomics, cognitive ergonomics, and organizational ergonomics. We decided to not include RFs that the IEA would include in 'organizational ergonomics' in the Human class. We choose to classify these in the Enterprise class as the operator does not have direct control over these factors. The IEA, does not explicitly speak of psychosocial factors. Yet this is a term, specifically related to psychosocial risk, which is widely used by the EU-OSHA. The EU-OSHA defines psychosocial risk on their website as "Psychosocial risks arise from poor work design, organisation and management, as well as a poor social context of work, and they may result in negative psychological, physical and social outcomes such as work-related stress, burnout or depression (European Agency for Safety and Health at Work, n.d.)". Although psychosocial as described by EU-OSHA, seems to include aspects of cognitive ergonomics and organizational ergonomics, we choose to label psychosocial as a separate subclass next to physical ergonomics and cognitive ergonomics:

- Psychosocial (37 or 54% of all identified RFs in Human): RF related to psychological and social factors. Typical topics that were included in this subclass are:
  - o Trust: potential risk associated with the acceptance of the cobot. There can be too little trust (distrust, i.e. due to false alarms) and too much trust (overreliance).

- o Human error: unintended use (deliberate or not, for instance, sabotage, vandalism) or mode error by the human, such as inadvertent activation of cobot modes or unintended re-start of cobot system.
- o Work-related stress: as defined by EU-OSHA "excessive and prolonged pressure and demands that exceed the worker's perceived resources, capabilities and skills to cope " (OSHWiki, n.d.). This class contains for instance work-related stress for the operator due to robot characteristics (i.e. speed, size, etc.) and/or unpredicted robot movement or due to reduced inter-human communication or due to the risk of job loss.

- Cognitive ergonomics (19 or 28% of all identified RFs in Human): RFs linked with mental processes. Included in this class were RFs related to:
  - o Cognitive (under-over) workload, for instance, under load due to monotony or overload due to increased knowledge demands.
  - o Loss of Situation Awareness (SA). SA is understood as the "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" as defined by Endsley (Endsley, 1995, p. 36). Insufficient SA can lead to dangerous situations as the operator might be incapable of reacting adequately to system malfunctions (Wolffgramm et al., 2019).
- Physical ergonomics (12 or 18% of all identified RFs in Human): RFs for the operator that is related to the physical workload and could cause musculoskeletal disorders (MSD), for instance as the result of an unergonomic working posture or work interface.

Although the list of keywords for the literature review did not explicitly contain psychosocial or any of the underlying topics that we classified as psychosocial, it is striking to observe that 18 out of 29 (62%) analyzed documents refer to psychosocial RFs. This confirms the growing need to include these RFs in risk identification and safety assessment methods for HRC. Human-related risk factors are mentioned in ISO 15066 and include stress, fatigue, or lack of concentration as a result of a collaborative operation. ISO sees these as elements to be considered in the factors related to ergonomics and human interface with the equipment and thus they seem to be more related to physical aspects. However, the draft update of the ISO 10218 standard, which is adapted to cover "requirements and guidelines for the inherently safe design, protective measures, and information for use of robots for an industrial environment." (ISO, 2020a, p. 1), does not mention any guidelines related to psychosocial risk factors. A major challenge related to the complex nature of psychosocial hazards is how to assess them and how to implement adequate measures in operational practices (Schuller, 2019).

#### 4.2.4. Collaborative workspace

The Collaborative workspace is, in line with ISO TS 15066, defined as the physical area in which the operator and robot collaborate (ISO, 2016). The authors of this paper decided to label the collaborative workspace as a separate class since this is where the actual interaction between humans and cobots takes place and where unexpected events can occur that are not immediately attributable to the human or the design of the cobot. This class represents 36 or 14% of all identified RFs and two subclasses were distinguished:

- Physical design (33 or 92% of all RFs identified in Collaborative Workspace): the physical and spatial design of the workspace includes RFs related to:
  - o The access and clearance: the processes and mechanisms that control who can enter the collaborative workspace
  - o The layout of the workspace: for instance the (unsafe) placement of equipment/machinery
  - o Hazardous obstacles/objects/substances in the workspace that can lead to occlusion, tripping, etc.
- Maintenance (3 or 8% of all RFs identified in Collaborative Workspace): referring to the risk pertaining to the maintenance of the cobot or the risk that maintenance employees can run when working in a collaborative workspace.

RF concerning the physical design of the workspace reveals to be the most prevalent. These RFs are also extensively mentioned by the ISO standards (ISO, 2016, 2020b).

In the ISO standard, maintenance is associated with the control of access, so it can be argued whether it is advisable to create a separate subclass. We decided to keep the maintenance subclass, because of the importance of the potential risk that is associated with maintenance activities (Jansen et al., 2018) and the special attention that needs to be given to the maintenance employees, other than the operator (Steijn et al., 2016).

#### 4.2.5. Enterprise

Since we are looking into industrial applications of HRC, we choose to use the term Enterprise as the label for the class that describes the legal entity and having an economic purpose, in which the HRC takes place. This term was preferred over the more general term 'organization', as the latter can also have a broader meaning, governments can for instance also be considered as a kind of organization. The adjective 'organizational' is used to refer to the way the enterprise is organized. The Enterprise class represents 34 or 13% of all identified RFs, the subclasses are:

- Ethics (12 or 35% of all identified RFs in Enterprise) are understood as the moral principles that govern the enterprise strategy and operations and includes topics such as:
  - o Social acceptance, for instance, the consequences of introducing a cobot within the group of people working with a cobot. We distinguish the risk factors related to the cobot acceptance of the individual operator (classified as psychosocial) with the role of the enterprise in considering the broader acceptance of cobots in the enterprise. For instance, when introducing cobots on the work floor did the management consider how there could be a difference in reaction between employees included in a cobot pilot project and the other employees who are not part of the pilot? The latter group might feel excluded and perhaps act aggressively towards the cobot causing a risk. Or operators might feel pressured to accept to work with a cobot, introducing stress and anxiety which could negatively influence their well-being.
  - o Privacy is related to the consequences of collecting and using data registered via cobot systems. For instance, what are the principles that the enterprise follows related to the possibility to increase surveillance as a possible result of the data capturing by the cobot? And consequently, how will the operator react when conscious of this monitoring by the cobot application?
  - o Algorithmic decision-making refers to the consequences of deciding without human involvement, using algorithms that steer the cobot. Reference is made for instance to how a lack of transparency about the way AI is analyzing the data could lead to unpredictable and potentially unsafe situations (Stacey et al., 2018).
- Organizational ergonomics (12 or 35% of all identified RFs in Enterprise) is related to organizational structures, policies, and processes of the enterprise potentially causing a risk to the HRC, as defined by the IEA (The International Ergonomics Association, n.d.). This subclass includes RF associated with:
  - o Lack of training to work with a cobot. A potential safety risk lurks behind the deskilling of work (Moore & Starren, 2019) as a result of the increased automation and (over)reliance on technology, and operators no longer need to specialize or are not sufficiently trained in coping with issues that go beyond their specific task. While this is good for the company's efficiency in production, lot size methods have led to significant OSH risks in that that they

deskill workers, because skilled labor is needed only to design the on-the-spot training programs used by those workers who no longer need to specialize themselves.
- o Work design, more particularly the specific organization of work (individual, teamwork, management) and working times that might influence risk.

- Technology and digitization strategy (8 or 24% of all identified RFs in Enterprise) is understood as the high-level strategy and plan that is concerned with the introduction and adoption of (new) technology. For instance, insufficient communication on the technology agenda can lead to a lack of acceptance of working with a cobot.
- Safety strategy (2 or 6% of all identified RFs in Enterprise) is the enterprise strategy and plan that is concerned with workers' safety. For instance, limitations in adapting existing safety assessments as the result of a cobot introduction can lead to risks for the operator.

The identified RFs that were classified as Enterprise, reflect some of the implementation challenges of new, advanced technologies not only from a technical point of view but also from a human factors perspective (Charalambous et al., 2015). Charalambous et al. identified seven key organizational human factors to be considered for the implementation of industrial HRC (Charalambous et al., 2015): "(i) communication of the change to employees, (ii) operator participation in implementation, (iii) training and development of workforce, (iv) existence of a process champion, (v) organisational flexibility through employee empowerment, (vi) senior management commitment and support and (vii) impact of union involvement."

Of these seven factors, two were explicitly identified in our survey: the need to consider communicating the change to employees and training. The role of operator participation as an element that might influence operator safety was not addressed by the papers in our survey. Charalambous et al. do not refer to the potential safety consequences of the lack of operator participation but found that operator involvement is a catalyst for the successful implementation of automation (Charalambous et al., 2015). Operator involvement has been included when discussing the safe design of Industry 4.0 work systems (Kadir et al., 2019; Pacaux-Lemoine et al., 2017) and has been linked with operational performance (Kadir & Broberg, 2020). Worker involvement and participation is a topic also discussed in STS literature, particularly in the participatory design approach, related to user participation in the development of technology (Klemsdal et al., 2017). Contemporary systems thinking inspired safety approaches such as Safety-II considers the involvement of the people directly related to the work as an important factor to reduce the gap between how the work was conceived (work-as-imagined) and how the execution takes place (work-as- done) (EUROCONTROL, 2014).

The predominance of RFs related to ethics stands out. Although the importance of social acceptance of technology in general, is well described as part of technology acceptance (Bröhl et al., 2016; Charalambous et al., 2015; Venkatesh & Bala, 2008), there is hardly any reference to HRC. Sabattini et al. refer to participation as an ethical dimension for an inclusive human–machine system. (Sabattini et al., 2017).

In machine ethics, researchers look into ethical issues that involve intelligent systems such as robots (Kose, 2018). Robot ethics is becoming an increasingly popular topic of investigation and discussion in society, Fletcher et al. suggest that there is little relevance or relatedness to industrial robotics and insufficient concern in the industrial automation community (Fletcher et al., 2019). This research domain also discusses safety issues linked with AI and ensuring safe AI-based systems (Kose, 2018). The topic of ethics in AI-enhanced technology is also high on the agenda of the European Commission (European Commission, 2018). The EU-OSHA commissioned a report looking into the use of AI-enhanced tools and applications in workplaces and what the implications are for workers' occupational safety and health, including for HRC (Moore & Starren, 2019). It is recognized that on the one hand AI can help reduce risk in HRC and on the other hand can create safety risks in the physical, cognitive and social realm (Moore & Starren, 2019). Regarding safety, the EU Commission Communication on "Building Trust in Human-Centric Artificial Intelligence" states that "AI systems should integrate safety and security-by-design mechanisms to ensure that they are verifiably safe at every step, taking at heart the physical and mental safety of all concerned" (European Commission, 2020, p. 3). Related to Industry 4.0 specific technological advancements, AI will also be more and more used to 'enhance' the human in the collaborative collaboration resulting in what is described in the literature as an "Augmented Operator" (Pereira & Romero, 2017) and "Operator 4.0"(Peruzzini et al., 2020; Romero et al., 2016).

#### 4.2.6. External

Even if only three RFs were classified in this class, it was decided to keep it as a separate class to reflect RFs related to conditions and events that originate outside the enterprise and are not under the control of the enterprise. Two subclasses were distinguished:

- Regulatory related to regulations issued by the government (directives, legislation) or any other recognized official body (ISO, EU-OSH, ILO …). For instance, important RFs here include vagueness of the legislation in such a way that it is difficult to translate into concrete safety guidelines in an industrial setting.
- Environmental conditions are RFs related to weather conditions that might affect HRC in the collaborative workspace (for instance direct sunlight might create occlusion or excessive temperature).

New emerging risks related to Industry 4.0 in general and HRC, in particular, are present in several of the identified classes, exemplified by cyber risk in Technology, psychosocial aspects in Human (e.g. robot acceptance), and new ethical challenges in Enterprise (i.e. social acceptance and algorithmic decision making). New emerging risks have been the subject of investigation in recent research and pose several challenges (Jain et al., 2018). Brocal et al. propose a gradation of the level of emerging risk to inform risk management, but the dynamic nature of uncertainty still needs to be further researched (Brocal et al., 2021). Further exploration of possible links between classes such as well-being and participation was not in the scope of this investigation.

### 4.3. System-wide properties of the classification

As a result of our investigation, the resulting five classes are Human, Technology, Collaborative Workspace, Enterprise, and External. The Collaborative Workspace is at the center of our investigation since it is here that the HRC takes place and risks for the operators will manifest themselves, regardless of whether they originated in the workspace or by one of the other dimensions. The Collaborative Workspace cannot exist without the Human, Technology, Enterprise, or External dimension. This could suggest a different level of hierarchy for the Collaborative Workspace, it is as if the Collaborative Workspace has to be 'fed' or supported by the other four dimensions to enable its existence. The relationship between the underlying RFs and the five dimensions is a topic for future research. The substance of the five dimensions is provided by the previously discussed subclasses.

In Section 1.3 we established the need for a system-wide view on RFs for HRC and in Section 2.3 we discussed system-wide properties through the lens of STS and established three determining STS dimensions needed to govern OHS in HRC: Human, Organizational and Technological. Comparing the five classes against the determining dimensions of contemporary STS shows that these classes reflect the minimum three STS dimensions: Human, Technological, and the class that was labeled 'Enterprise' corresponds to the Organizational STS dimension. Environmental (understood as part of the External class) was also an important STS dimension and thus strengthens the system-wide perspective of the five classes.

## 5. Suggestions for future research

The scope of this paper is to identify RFs from the literature of the past decade. The further analysis of the importance of the RFs and their classification is an important next step. This step is also necessary to achieve the ultimate goal which is to develop a practical and easy-to-use tool to support risk assessment in the early stage of the design of an intended human-robot collaboration.

A possible approach to get insights on the RFs' importance is an in-depth stakeholder analysis. This analysis could be based on a Delphi approach to collect stakeholder opinions and to determine the extent to which stakeholders agree. Stakeholders can be identified internally (manufacturer) and externally (e.g. industry specialists and safety consultants). A stakeholder analysis will also allow deriving possible guidelines and recommendations for engineers and researchers.

In line with design science, the resulting framework will need to be evaluated, validated and field-tested (Verschuren & Hartog, 2005).

## 6. Summary and conclusion

We first defended the need to take a broader perspective beyond technical and physical safeguards by looking at cobots from a system-wide perspective. Looking through the lens of STS at the meaning of system-wide properties, we established three determining STS dimensions needed to also govern safety in HRC. Then this paper presented the identification and classification of RFs for HRC. Finally, the system-wide properties of the resulting five classes were discussed. Thus, the two research questions defined in the introduction were successfully answered.

Applying an inductive approach by using the Constant Comparison method, five classes resulted from the analysis. Other classifications have been proposed from different angles in the literature. For instance, a conceptual framework to evaluate the collaboration between humans and robots has been proposed by Gervasi et al. resulting in eight different HRC latent dimensions: autonomy, information exchange, adaptivity and training, team organization, task, human factors, ethics, and cybersecurity (Gervasi et al., 2020). Within these dimensions, safety is only specifically addressed within the task and ethics dimensions. A prior classification of hazards for HRC has been made by Khalid et al. who proposed the following three sources of potential hazards: hazards from robot during collaboration; hazards from the industrial process during collaboration and hazards from robot control system malfunction during collaboration (Khalid et al., 2017). This classification focuses on the technological aspects. The reigning focus on Technological RFs leads to ambiguous insights. On the one hand, this predominance is plausible as these factors are essential to ensure the operator's safety. On the other hand, the technology advancements lead to new risks, such as cyber risk, which would argue for even more Technological RFs, preferably reflected in regulations. The draft version of the updated ISO 10218 does include cybersecurity but the modified standard is not yet adopted confirming that regulation can hardly keep track of technological advancement and is more reactive than proactive (Badri et al., 2018).

Only the papers by Moore & Starren and Steijn et al. (Moore & Starren, 2019; Steijn et al., 2016) discuss at least one of the subclasses within the five classes proposed in this paper, this illustrates the contribution of our investigation and the need to investigate this further.

Although the list of keywords for the literature did not explicitly contain psychosocial or any of the underlying topics that we classified as psychosocial, it is striking to observe that 18 out of 29 (62%) analyzed documents refer to psychosocial RFs. This confirms the growing need to include these RFs in risk identification and safety assessment methods and OSH regulation for advanced technologies such as HRC (Polak-Sopinska et al., 2020) (Mercader Uguina & Muñoz Ruiz, 2019).

In the Enterprise class, the observed importance of ethics is also underscored by the recent policy documents of the EU commission (European Commission, 2018) and EU-OSHA (Moore & Starren, 2019). Involvement and participation of the operator specifically related to HRC RFs is an area that merits more attention, including how it can be linked with human well-being.

This paper establishes the need to at least enrich the EU-OSHA definition of OSH. Depending on the interpretation of the definition it can be argued that the RFs captured in our classification will eventually impact the work activity in the collaborative workspace. We see several challenges going forward. One challenge will be the agility and adaptability of legislation to at least keep track of RFs emerging from continuously changing technologies such as robotics and to translate them into practical applicable tools for enterprises and design engineers and secondly the measurement of the new emerging and sometimes less technological risks.

## CRediT authorship contribution statement

**Nicole Berx:** Conceptualization, Methodology, Visualization, Writing – original draft. **Wilm Decré:** Methodology, Writing – review & editing. **Ido Morag:** Methodology, Writing – review & editing. **Peter Chemweno:** Methodology, Writing – review & editing. **Liliane Pintelon:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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Nicole Berx and Wilm Decré are members of Flanders Make@KU Leuven - core lab ROB.


## Appendix A. List of papers and documents analyzed

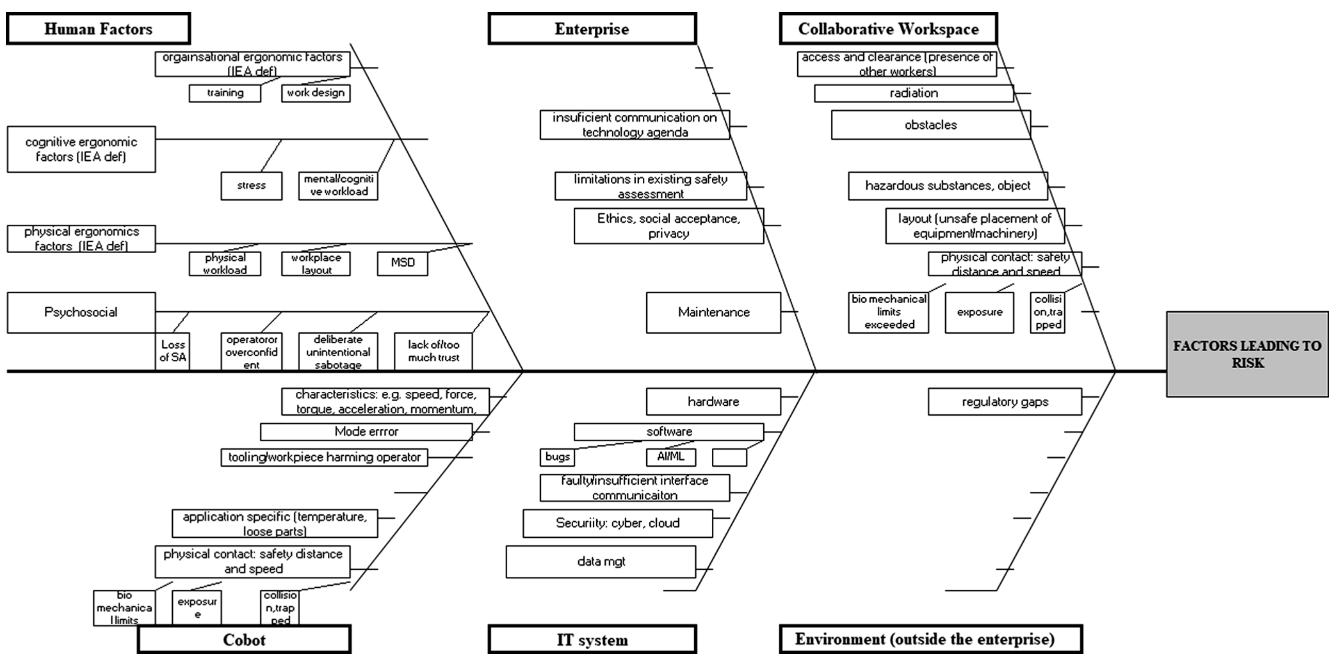
| Author(s) Reference | Paper Title | Year |
|---|---|---|
| (Gualtieri et al., 2021) | Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review. | 2021 |
| (Neumann et al., 2021) | Industry 4.0 and the Human Factor – A Systems Framework and Analysis Methodology for Successful Development. | 2021 |
| (Chemweno et al., 2020) | Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems. | 2020 |
| (Colim et al., 2020) | Towards an Ergonomic Assessment Framework for Industrial Assembly Workstations-A Case Study. | 2020 |
| (Gervasi et al., 2020) | A Conceptual Framework to Evaluate Human-Robot Collaboration. | 2020 |
| (Hanna et al., 2020) | Towards safe human robot collaboration - Risk assessment of intelligent automation. | 2020 |
| (ISO, 2020b) | DRAFT INTERNATIONAL STANDARD ISO / DIS 10218-2 Robotics — Safety Requirements for Robot Systems in an Industrial Environment — Part 2 : Robot Systems, Robot Applications and Robot Cells. | 2020 |

(continued on next page)

(*continued*)

| Author(s) Reference | Paper Title | Year |
|---|---|---|
| (ISO, 2020a) | DRAFT INTERNATIONAL STANDARD ISO / DIS 10218-1 Robotics — Safety Requirements for Robot Systems in an Industrial Environment — Part 1 : Robots. | 2020 |
| (Kopp et al., 2021) | Success Factors for Introducing Industrial Human-Robot Interaction in Practice: An Empirically Driven Framework. | 2021 |
| (Zacharaki et al., 2020) | Safety Bounds in Human Robot Interaction: A Survey. | 2020 |
| (Aldini et al., 2019) | A risk reduction framework for design of physical human-robot collaboration | 2019 |
| (Antonelli & Stadnicka, 2019) | Predicting and preventing mistakes in human-robot collaborative assembly | 2019 |
| (Gopinath & Johansen, 2019) | Understanding situational and mode awareness for safe human-robot collaboration: case studies on assembly applications. | 2019 |
| (Hentout et al., 2019) | Human-robot interaction in industrial collaborative robotics: a literature review of the decade 2008-2017. | 2019 |
| (Moore & Starren, 2019) | Discussion Paper OSH and the Future of Work: Benefits and Risks of Artificial Intelligence Tools in Workplaces | 2019 |
| (Nikolakis et al., 2019) | A cyber physical system (CPS) approach for safe human-robot collaboration in a shared workplace. | 2019 |
| (Aaltonen et al., 2018) | Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry. | 2018 |
| (Gopinath et al., 2018) | Collaborative Assembly on a Continuously Moving Line - An Automotive Case Study. | 2018 |
| (Jansen et al., 2018) | Emergent Risks To Workplace Safety ; Working in the Same Space As a Cobot. | 2018 |
| (Leso et al., 2018) | The occupational health and safety dimension of Industry 4.0. | 2018 |
| (Stacey et al., 2018) | Foresight on new and emerging occupational safety and health risks associated with information and communication technologies and work location by 2025. | 2018 |
| (Villani et al., 2018) | Survey on human-robot collaboration in industrial settings: Safety, intuitive interfaces and applications. | 2018 |
| (Grahn et al., 2017) | Safety Assessment Strategy for Collaborative Robot Installations. | 2017 |
| (Guiochet et al., 2017) | Safety-Critical Advanced Robots: A Survey. | 2017 |
| (Khalid et al., 2017) | Implementing Safety and Security Concepts for Human-Robot Collaboration in the context of Industry 4.0. | 2017 |
| (Koppenborg et al., 2017) | Effects of movement speed and predictability in human-robot collaboration. | 2017 |
| (Lasota et al., 2017) | A Survey of Methods for Safe Human-Robot Interaction. | 2017 |
| (ISO, 2016) | TECHNICAL SPECIFICATION ISO / TS 15066 Robots and Robotic Devices —Collaborative Robots. | 2016 |
| (Steijn et al., 2016) | Emergent Risk to Workplace Safety as a Result of the Use of Robots in the Work Place. | 2016 |
| (Michalos et al., 2015) | Design Considerations for Safe Human-robot Collaborative Workplaces. | 2015 |
| (Missala, 2014) | Paradigms and Safety Requirements for a New Generation of Workplace Equipment. | 2014 |
| (Matthias et al., 2011) | Safety of collaborative industrial robots: Certification possibilities for a collaborative assembly robot concept. | 2011 |

## Appendix B. Illustration of intermediate Ishikawa diagram




## Appendix C. Full list of all identified Risk Factors

| # | Identified hazard or risk factor (as described by author) | Author |
|---|---|---|
| 1 | Application related (e.g. Operator is in the blasting stream; Nozzle is released from tool while blasting and hits the operator) | Aldini, et al. 2019 |
| 2 | unexpected humans in the workspace | Aldini, et al. 2019 |
| 3 | workspace occluded | Aldini, et al. 2019 |
| 4 | Configuration kinematic singularities | Aldini, et al. 2019 |

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| # | Identified hazard or risk factor (as described by author) | Author |
|---|---|---|
| 5 | Configuration self collision | Aldini, et al. 2019 |
| 6 | Environment- robot collision | Aldini, et al. 2019 |
| 7 | Forces over limit | Aldini, et al. 2019 |
| 8 | Human pinched by robot | Aldini, et al. 2019 |
| 9 | Human trapped | Aldini, et al. 2019 |
| 10 | Human-robot collision | Aldini, et al. 2019 |
| 11 | Jerky movements | Aldini, et al. 2019 |
| 12 | Multiple robot agents collision | Aldini, et al. 2019 |
| 13 | Psychological distress | Aldini, et al. 2019 |
| 14 | Tool harming or damaging agent or environment | Aldini, et al. 2019 |
| 15 | Uncomfortable posture | Aldini, et al. 2019 |
| 16 | Unergonomic interface | Aldini, et al. 2019 |
| 17 | Unintended use | Aldini, et al. 2019 |
| 18 | Vibrations | Aldini, et al. 2019 |
| 19 | multiple humans in the workspace | Aldini, et al. 2019 |
| 20 | location of the robot may impact the perception of the human towards the system. (possibly causing distress) | Aldini, et al. 2019 |
| 21 | "subtle risk: .... In automatic assembly nonconformities are generated because of program errors " | Antonelli, 2019 |
| 22 | "subtle risk: defects caused by mistakes in the communication between human and robot. In manual assembly mostly the human is responsible for errors, automatic assembly nonconformities are generated because of ... wrong handling or joining." | Antonelli, 2019 |
| 23 | "A link between cognitive workload conditions (related to task design) to human fatigue, which negatively affects the performance of a human operator leading to possible lapses in judgement and potential errors leading to accident events is discussed in literature, e.g. see Guastello et al. (Guastello et al., 2012)." | Chemweno, 2020 |
| 24 | "Although intuitive, such strategies often overlook salient triggers associated with collision hazards, including hazards embedded in the work environment, such as physical obstacles, or protrusions on the workpiece, etc. (Guo and Zhang, 2014; Savkin and C, Wang, 2014). The review studies discussed in this section shows a tendency towards hardware or control-related design safeguards which are primarily implemented for collision avoidance (p4)" | Chemweno, 2020 |
| 25 | "Design of the collaborative workplace, access and clearance (ISO 15066 Clause 5.3)" | Chemweno, 2020 |
| 26 | "factors such as physical strain the actuator places on the neck muscle of a user, potentially injuring the user of the actuator." | Chemweno, 2020 |
| 27 | "hazardous contact with end effector or tooling" | Chemweno, 2020 |
| 28 | "To assess and quantify potential controller-related errors, formal verification methods are potentially useful for verifying that the mathematical scaled model of the robot controller is inherently safe." | Chemweno, 2020 |
| 29 | "Cybersecurity is the process of protecting information by preventing, detecting, and responding to attacks [58]. As technology grows, robots are increasingly connected to the network, constantly exchanging information [61]. This makes robots exposed to cyber attacks that can lead to data leakage, malfunction, or even damage to peo- ple or property." | Gervasi, 2020 |
| 30 | "Social acceptance indicates the perception of the collaborative robotic system within a community. It is important that the community in which the collaborative robot is intro- duced has a good level of predisposition for such forms of technology. Otherwise, some of the main risks could be poor robot usage or frustration." | Gervasi, 2020 |
| 31 | "The introduction of robots in some contexts is not only associated with physical hazards, but also with ethical hazards [80]. According to BS 8611 [18], ethical hazards are "potential source of ethical harm", i.e., "anything likely to compromise psychological and/or societal and environmental well-being". Sub-dimensions: social impact and social acceptance (Table 10). Social impact refers to the consequences of introducing a collaborative robotic system within a community. The introduction of a collaborative robot in a work context can lead to a change in the roles of some workers or even job losses. Studying these effects is critical to understanding how to introduce collaborative robots while minimizing the impact on workers. A first evaluation of this sub-dimension is provided by the three-level scale reported in Table 10, which follows the well-being of humans" | Gervasi, 2020 |
| 32 | "the physical interaction with a robot introduces new risks in a working space, mainly related to collisions [26]." | Gervasi, 2020 |
| 33 | "Faulty feedback: As noted by Sarter [20], in complex human-automation collaborative systems, effective feedback between the human and the automation device is critical to avoid hazardous situations." | Gopinath et al, 2018 |
| 34 | "Functions automated at low automation level leads to overload and fatigue resulting in the occurrence of mistakes [29] or other unanticipated situations. In addition to overload and underload, Eberts and Salvendy [30] lists factors associated with decision making and interaction errors. They state that these cognitive factors can be used in the design of automation systems to reduce the probability of human errors" | Gopinath, 2019 |
| 35 | "hazards associated with loss in situational awareness" | Gopinath, 2019 |
| 36 | "The effect of systems with multiple mode of operation can result in accidents due to the higher risk of inadvertent activation of modes (mode-error) by the operator. Mode-error can also occur if an operator attempts to change the mode but instead activates an unanticipated function because of a lack of awareness of the system state [28]." | Gopinath, 2019 |
| 37 | "The risks associated with unintentional or uncontrolled motion is very high and is attributed to the physical size of the robot" | Gopinath, 2019 |
| 38 | Physical fences requires deliberate actions and does not allow for easy entry to a hazardous space, thereby mitigating risks associated with automation misuse. | Gopinath, 2019 |
| 39 | "detect limitation in existing safety practices, in order to ensure effective safety assessment considerations for collaborative installations: ie to integrate assessment of collaboratiove operations, be integrated in pilot studies, during installation reconfiguration and operation stage" | Grahn et al. 2017 |
| 40 | "Functions for robot control are increasingly moving to the "cloud", this means that lacking IT-security also directly results in operator safety hazards" | Grahn et al. 2017 |
| 41 | "One has to deal with the fact that robots in collaborative installations must comply with at least two different, potentially conflicting sets of instructions; programmed instructions and physical, passive or active, instructions from the operator. One must also deal with the fact that delivery of the physical instructions from operators to robots may take place through multiple communication channels as force, voice, signs and so so on. All these instructions can be conflicting and pose a potential risk factor." | Grahn et al. 2017 |
| 42 | "Regardless of the theoretical high-safety level, a collaborative installation must be designed so that operators feel it is acceptable to work in the immediate vicinity of a robot." | Grahn et al. 2017 |
| 43 | "Another important part will be the acceptability of the robot systems by the human coworkers. In fact, a more or less closed interaction produces several advantages but also introduces new forms of discomfort for the operators at the same time." | Gualtieri, 2021 |
| 44 | "Contact Avoidance is to ensure operators safety (in terms of mechanical risk) by pre-empting dangerous contacts using preventive methodologies and systems." | Gualtieri, 2021 |
| 45 | "Contact Detection and Mitigation is to ensure operators safety (in terms of mechanical risk) through the reduction of the collision energy which can be exchanged during unwonted or unexpected human–robot contacts." | Gualtieri, 2021 |
| 46 | "The role of ergonomics in HRI should be to support humans in the reduction of work-related biomechanical and cognitive overload without introducing new hazards for the health and safety of the op- erators (e.g. work-related stress which potentially could arise from the interaction with the robot systems)." | Gualtieri, 2021 |
| 47 | "work- related psychosocial risks which could potentially arise from the sharing of activities and workspaces" | Gualtieri, 2021 |
| 48 | | Guiochet et al. 2017 |

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| # | Identified hazard or risk factor (as described by author) | Author |
|---|---|---|
| | "Additionally to the intrinsic decisional difficulty, it is also important to mention the residual faults (bugs) in the software as another source of hazard." | |
| 49 | "Detecting plan execution errors is known in robotics as execution monitoring [124,… These works actually do not focus on faults in the planner itself but rather on the planner capacity to cover errors coming from other layers. For instance, in [127], the decision level integrates mechanisms to deal with environment hazards. The planner has a model of reachable states, and it checks if safety properties are respected. It computes a distance between intermediary states and hazardous states. Authors of [128] point out that the decisional layer may also cover faults in the hardware layer." | Guiochet et al. 2017 |
| 50 | "Regarding the interaction, and the proximity with users, an example of a new hazard is a bad synchronization or communication mishap with robot interface." | Guiochet et al. 2017 |
| 51 | "... is common if the control sequences are complex. It can happen in the case when the operator is picking and entering the bolts and the robot is tightening the bolts sequentially. If the sequence of the operator and the robot is not synchronized it may lead to that some steps are being missed, and that the robot tool may hit the operator while he/she is stressing to enter the bolts." | Hanna, 2020 |
| 52 | "a common challenge for any type of automation system, where a hardware failure (or control error) make a robot drop what it is carrying, but can have greater consequences if it happens during a true collaborative operation. This failure can cause e.g. the heavy ladder frame to overturn on the operator's body or legs and injure him." | Hanna, 2020 |
| 53 | "is initiated by the operator who may not be aware of the robot state, which then moves in a direction not anticipated by the operator, probably due to communication failure, which lead to collision between the robot and the operator." | Hanna, 2020 |
| 54 | "may occur when the robot and the operator share a workspace and execute their tasks in parallel, when e.g. a sensor failure makes the robot change its path unintentionally and hits the operator." | Hanna, 2020 |
| 55 | "relates to troubleshooting situations. It can occur e.g when the robot fails to attach to the oil filter tool, due to changed tool position and the robot stops. The operator may step in and try to correct without communicating with the system and suddenly the robot starts to move and collide with the operator." | Hanna, 2020 |
| 56 | "A robot could injure a human by two different manners [136]: (i) physical injuries caused by unintentional or unwanted contact between the human and robot if the exerted forces exceed a certain threshold. ... many types of injuries could occur [135]: (a) contact with a sharp or abrasive surfaces may cause cuts or abrasions, (b) manipulator pinchpointsordirectcrush loadsmay causeserious injuries such as bone fracture, and (c) potential impact with large loads may cause more serious injury or even death.Therobotscan move theirarmsortheirbodies byforce, very quickly, and often deal with dangerous and sharp tools. This represents a threat to all humans surrounding robots [32,101]. " | Hentout et al. 2019 |
| 57 | "In addition, the dangerous behavior of these systems, caused by failure or extreme environmental conditions, can have catastrophic consequences [102]" | Hentout et al. 2019 |
| 58 | "One of the major challenges in an industrial HRI is how to transfer information between the humans and robots using existing equipments and approved by secu- rity [286,298]." | Hentout et al. 2019 |
| 59 | (ii) indirect or psychological injuries caused by many factors such as robot appearance, embodiment, gaze, speech, posture [134,315]. | Hentout et al. 2019 |
| 60 | "The addition of features to support cybersecurity shall be considered." | ISO 10218-1 |
| 61 | failures to the mechanical and electrical components | ISO 10218-1 |
| 62 | inappropriate location of operating control and of componentsthat require access for anticipated maintenance actions | ISO 10218-1 |
| 63 | loose clothing, long hair | ISO 10218-1 |
| 64 | movement of any robot parts | ISO 10218-1 |
| 65 | movements of additional axis, rotational motion of any robot axes | ISO 10218-1 |
| 66 | movements of any part ot the manipulator | ISO 10218-1 |
| 67 | servicing, lubrication and changing components that are coverd in fluids; cooling and process fluids | ISO 10218-1 |
| 68 | unexpected release of potential energy from stored sources | ISO 10218-1 |
| 69 | Risk of a person falling in the landing when a robot is operating a vertical transfer | ISO 10218-2 |
| 70 | end-effector exchange (or unintended disconnection), leading to hazard | ISO 10218-2 |
| 71 | Overload in lifting work pieces or tools, or moving or lifting robots | ISO 10218-2 |
| 72 | sharp edges on end-effector resulting in unacceptable contact force/power | ISO 10218-2 |
| 73 | loss or restoration of power creating a hazard for operator | ISO 10218-2 |
| 74 | crushing between moving parts | ISO 10218-2 |
| 75 | hazardous exposure to laser radiation | ISO 10218-2 |
| 76 | hazardous material handling (entanglement, falling material) | ISO 10218-2 |
| 77 | hazards due to the operation of manual (un)load station | ISO 10218-2 |
| 78 | application related hazards (eg ejected parts, welding sparks) | ISO 10218-2 |
| 79 | faulty presence sensing | ISO 10218-2 |
| 80 | hazards from ajacent cells | ISO 10218-2 |
| 81 | "When darkness or shadows due to lighting cause hazardous situation(s) for operators to perform tasks … Hazard zones where frequent inspection, adjustment or maintenance is required, shall be provided with appropriate additional lighting" | ISO10218-2 |
| 82 | "In general: safe access to where intervention is necessary during maintenance needs to be provided. Ex: During maintenance: the system shall be provided with the local means of controlling and isolating hazardous energy, eg by providing protective measures" | ISO10218-2 |
| 83 | delineation of the restricted space and collaborative workspaces; | ISO15066 |
| 84 | description of the tasks including the required training and skills of an operator; | ISO15066 |
| 85 | influences on the collaborative workspace (e.g. material storage, work flow requirements, obstacles); | ISO15066 |
| 86 | the intended and reasonably foreseeable contact(s) between portions of the robot system and an operator; | ISO15066 |
| 87 | " clarity of controls;" | ISO15066 |
| 88 | "acceptable biomechanical limits under intended operation and reasonably foreseeable misuse" | ISO15066 |
| 89 | "Additional hazards (e.g. fumes, gases, chemicals and hot materials) can be created by the specific collaborative applications (e.g. welding, assembly, grinding, or milling). These hazards shall be addressed on an individual basis through a risk assessment for the specific collaborative application." | ISO15066 |
| 90 | "deficiency in ergonomic design (e.g. resulting in loss of attention, improper operation)" | ISO15066 |
| 91 | "error or misuse (intentional or unintentional) by operator" | ISO15066 |
| 92 | "possible reflex behaviour of operator to operation of the robot system and related equipment" | ISO15066 |
| 93 | "possible stress, fatigue, or lack of concentration arising from the collaborative operation" | ISO15066 |
| 94 | "potential consequences of single or repetitive contacts" | ISO15066 |
| 95 | "robot characteristics (e.g. load, speed, force, momentum, torque, power, geometry, surface shape and material);" | ISO15066 |
| 96 | "the established limits (three dimensional) of the collaborative workspace" | ISO15066 |
| 97 | "The location of equipment and machinery should not introduce additional hazards. Safety-rated (5.3)" | ISO15066 |
| 98 | end-effector and workpiece hazards, including lack of ergonomic design, sharp edges, loss of workpiece, protrusions, working with tool changer; | ISO15066 |
| 99 | process-specific hazards (e.g. temperature, ejected parts, welding splatters); | ISO15066 |
| 100 | | ISO15066 |

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| # | Identified hazard or risk factor (as described by author) | Author |
|---|---|---|
| | starting and ending of collaborative operation;<br><br>2) transitions from collaborative operations to other types of operation | |
| 101 | identification of persons (groups) with access to the collaborative robot system; | ISO15066 |
| 102 | limitations caused by the required use of personal protective equipment; | ISO15066 |
| 103 | operator motion and location with respect to positioning of parts, orientation of structures (e.g. fixtures, building supports, walls) and location of hazards on fixtures; | ISO15066 |
| 104 | quasi-static contact conditions in the robot; | ISO15066 |
| 105 | fixture design, clamp placement and operation, other related hazards; | ISO15066 |
| 106 | operator location with respect to proximity of the robot (e.g. working under the robot); | ISO15066 |
| 107 | potential intended and unintended contact situations; | ISO15066 |
| 108 | the need for clearances around obstacles such as fixtures, equipment and building supports; | ISO15066 |
| 109 | a determination as to whether contact would be transient or quasi-static, and the parts of the operator's body that could be affected; | ISO15066 |
| 110 | accessibility for operators; | ISO15066 |
| 111 | restriction of access to authorized operators only; | ISO15066 |
| 112 | required training level and skills of the operator; | ISO15066 |
| 113 | the design and location of any manually controlled robot guiding device (e.g. accessibility, ergonomic, potential misuse, possible confusion from control and status indicators, etc.); | ISO15066 |
| 114 | access routes (e.g. paths taken by operators, material movement to the collaborative workspace); | ISO15066 |
| 115 | the influence and effects of the surroundings (e.g. where a protective cover has been removed from an adjacent machine, proximity of a laser cutter); | ISO15066 |
| 116 | hazards associated with slips, trips and falls (e.g. cable trays, cables, uneven surfaces, carts); | ISO15066 |
| 117 | Presence of other machines: "If other machines in the collaborative workspace present a hazard, then protective measures shall be applied in accordance with ISO 10218-2:2011, 5.11.2." (5.3) | ISO15066 |
| 118 | Risks associated with whole body trapping or crushing between the robot system and, for example, parts of buildings, structures, utilities, other machines, and equipment, shall be eliminated or safely controlled. (5.3) | ISO15066 |
| 119 | "...the environment in which the human-robot interaction takes place is an important factor in safe interaction between humans and robots,.." | Jansen, et al. 2018 |
| 120 | "A high degree of robot autonomy combined with a low mental workload can result in boredom,28 whereas a low degree of autonomy combined with a high mental workload could result in reduced situation awareness and performance." | Jansen, et al. 2018 |
| 121 | "A short power disruption during an emergency braking manoeuvre may involve a risk that the AGV will roll back and crush an operator." | Jansen, et al. 2018 |
| 122 | "Alongside the legal requirements of AGV designs and the integration of AGV systems in the workplace, another risk factor for interaction with AGVs is human error, ...." | Jansen, et al. 2018 |
| 123 | "Although the Machinery Directive requires that machines must be able to be overruled by humans, overruling an AGV can also pose a risk. In practice, some AGVs should not be able to be overruled by all users. A situation could occur, for example, in which an AGV shuts down during an emergency and overruling this could cause other hazards." | Jansen, et al. 2018 |
| 124 | "An effective safety culture is an important part of ensuring the safe use of automated systems. Employees should be trained in and informed of the use of the AGV and the safety risks involved in working with or nearby AGVs. Although it will not remove the source of the problem, separating logistic flows in the workplace will help to limit the probability of obstructions to AGVs in general." | Jansen, et al. 2018 |
| 125 | "Biomechanical criteria for power limitation for collaborative robots are set out in ISO 10218- 1, Section 5.10.5." | Jansen, et al. 2018 |
| 126 | "changes in preprogrammed trajectories are failed to be implemented in the cobot software (mapping technology)<br><br>Other ex p 37 "The AGVs that are purchased today are not universal; new and different versions are constantly being introduced to the market. The result is that a service engineer cannot always be sure if an AGV has the latest software, for example, which increases the risk of unpredictable robot behaviour." | Jansen, et al. 2018 |
| 127 | "Compared with robots that only provided information to the team, robots with social emotional skills improved the ability of employees to cope with stress and encouraged them to accept the robots' physiological sensors. Social Characteristics being: "social characteristics, e.g. appearance, emotions and personality (see also Breazeal, 2003). " | Jansen, et al. 2018 |
| 128 | "Human trust in cobots is based on image-building and experience. Too much trust ('The cobot can see me') can result in high-risk behaviour, whereas not enough trust can result in acceptance problems. Also, people tend to attribute human qualities to robots based on their appearance and behaviour"<br><br>"Trust in robots has also been found to be an important factor in the decisions that people make in high-risk situations."<br>"Several studies have shown the importance of trust in and acceptance of robots. Trust in robots has also been found to be an important factor in the decisions that people make in high-risk situations."<br>"Importance of Trust (leading to acceptance in Human-Robot teamwork: "Beer et al. (2012) consider that insight into the development of trust is vital when designing robots, which need to be regarded as 'social partners', since robots are not automatically accepted as work colleagues. The authors therefore say that further research is needed in order to understand and model the variables involved in the acceptance of robots (in relation to their degree of autonomy)." | Jansen, et al. 2018 |
| 129 | "In addition to the technical design constraints ..., various work factors are involved in the well-being of employees and their safety behaviour in certain work situations." "Pivotal human factors include the following: physical workload, cognitive workload and job satisfaction" | Jansen, et al. 2018 |
| 130 | "Incorrect and inappropriate use of robots appears to take place predominantly during night shifts. " | Jansen, et al. 2018 |
| 131 | "Operating systems cannot be certified. A risk of integrating software components in a standardized operating system is that it may result in unexpected interaction effects. These could pose a risk to the integrity of the system, particularly if open-source software is used. Software modules are often highly interdependent; the failure of a single module can affect the other systems." | Jansen, et al. 2018 |
| 132 | "Perception and interpretation of environmental factors are thus important in awareness of the working environment. It is important to improve people's situation awareness when collaborating with cobots. A" "A use case provides opportunities to examine the extent to which a cobot can help a human to improve his situation awareness in relation to safety risks." | Jansen, et al. 2018 |
| 133 | "Physical risks can be divided into two main categories:<br><br>1. Risks that arise from robot designs. (...) - High-speed collisions; managed by speed limiters and position controllers (zoning plan).<br>- Crush hazards (joints between which people can become crushed); this risk is managed by applying rounded forms in the design and it is determined by the amount of torque a cobot can apply (i.e. the maximum permitted resistance between an object and a cobot in a given zone, which is determined separately for each configuration (depending on the application)." | Jansen, et al. 2018 |
| 134 | "Physical risks can be divided into two main categories:<br><br>(...). 2. Risks that arise from the functional use of the AGV (tooling).<br>- Tooling; e.g. impact and speed are required to be lower at eye level than at stomach level.<br>- Battery voltage and acid risk; managed by zoning, e.g. by placing the battery in a separate compartment that cannot be accessed by the user" | Jansen, et al. 2018 |

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| # | Identified hazard or risk factor (as described by author) | Author |
|---|---|---|
| 135 | "risks due to robots becoming more intelligent as a result of Artificial Intelligence built into the software". "When implementing cobots in the workplace it is important to ascertain what capabilities they need in order to be able to interact safely with humans. An important point is that cognitive cobots display real-time, adaptive, anticipatory behaviour based on an observed situation and future circumstances (based on past experience). As regards AI, there is a difference between symbolic AI (usually logic-based, with explicit knowledge representations, enabling a human-robot shared mental model and situation awareness) and sub-symbolic AI (machine learning, which is more of a black box for the user). As regards machine learning, an important point is whether it is applied at design time or at run-time.". "machine learning can result in unpredictable behaviour on the part of the robot."<br><br>" Machine learning can create risks particularly if the current situation differs from the situation in which the learning originally took place (the learned model is not applicable to the current situation). Incorrect perception of the environment, or inappropriate response to unplanned situations faced by the robot, and erroneous reasoning by the robot or errors in the knowledge representation of the system in which the robot moves around, can cause incidents."<br>Further explained ao applied to AGV's: p 41 - 42 | Jansen, et al. 2018 |
| 136 | "Risks of software components can also be caused by uncertain factors in the working environment to which the robot is exposed (e.g. sensor degradation, unexpected human action, use of the robot in unstructured environments such as building sites or newly configured production lines)." | Jansen, et al. 2018 |
| 137 | "sensor degradation, also limitation of hardware (eg ref to Lidar technology/laser scanner on p 32) | Jansen, et al. 2018 |
| 138 | "software components can contain bugs resulting in high-risk situations, e.g. activation of an unintended movement by the robot" | Jansen, et al. 2018 |
| 139 | risk statuses " The following aspects will need to be considered carefully, among others:<br><br>- Safety interface. The creation of fault categories and a manageable number of aspects to be communicated.<br>- Redundancy. If a message is delivered more than once, there is a greater likelihood that it will be understood. The message should be delivered in several alternative physical forms (e.g. colour, shape, voice, print, etc.), because redundancy should not involve repetition. A traffic light is a good example of redundancy: the positions of the lights (top, middle, bottom) render the different colours (red, yellow, green) redundant.<br>- Clear distinction in modus shift. The interactive components must be so designed that they clearly indicate whether the AGV is braking or accelerating. As soon as the AGV enters fault mode (AGV out of action) or vice versa, it must be clear to the user what the cause of the fault is and what the implications are for the user (AGV out of action)."<br>- A human-robot interface (with detailed information about debugging, among others). The user (in this case the engineer) must also be informed of the risks and be able to distinguish between the following statuses: o Is the freedom of the AGV limited (autonomous mode) or not? o What is the AGV able/allowed to do in this situation?" | Jansen, et al. 2018 |
| 140 | "The use of sensors in busy environments can entail risks for the AGV's ability to detect objects and humans around it; an environment with many humans in it may produce more information than an AGV can process." | Jansen, et al. 2018 |
| 141 | "The user may become more confident in using the AGV, which can lead to less situational awareness (for example in case of unpredictable behaviour). In some cases, an AGV could display unexpected behaviour due to an error in the program code. In situations such as these, employees' confidence may influence their safety when interacting with the AGV. " | Jansen, et al. 2018 |
| 142 | "Their research showed that familiarity with robots resulted in various positive changes (including knowledge development and self-realization), despite the fact that employees had been mainly sceptical and uncertain about the potential for collaboration to begin with. Poor preparation for the introduction of robots in the workplace resulted not only in complex tasks but also in a number of emotional reactions, e.g. fear of dismissal and bullying." | Jansen, et al. 2018 |
| 143 | "Trust ('The robot can see me') can result in high-risk behaviour, whereas not enough trust can result in acceptance problems. People tend to attribute human qualities to robots based on their appearance and behaviour<br><br>P 43: "Mistrust of AGVs in the workplace was also discussed during the workshop. The interviews revealed that mistrust is primarily a potential risk during the implementation of the AGV. Mistrust as a result of negative experiences with AGVs is also a potential risk with possible consequences for the wellbeing of employees" | Jansen, et al. 2018 |
| 144 | "work stress" | Jansen, et al. 2018 |
| 145 | cognitive workload | Jansen, et al. 2018 |
| 146 | Software risk: "In addition to the risks relating to machine learning there is a potential risk of 'security breaches and intrusions' from outside as a result of the robot's internet links, which could cause the integrity of the software programming to be affected." | Jansen, et al. 2018 |
| 147 | " Hazards from robot characteristics, i.e., speed, force, torque, acceleration, momentum, power etc." | Khalid et al., 2017 |
| 148 | "Ergonomic design deficiency for operation and maintenance." | Khalid et al., 2017 |
| 149 | "Hazard from fast worker approach speed and robot's slow reaction time." | Khalid et al., 2017 |
| 150 | "Hazards from operator during reasonably foreseeable misuse of the system." | Khalid et al., 2017 |
| 151 | "Mental stress to operator due to robot characteristics (e,g., speed, inertia etc.) or due to the collaborative process" | Khalid et al., 2017 |
| 152 | "Sensitivity of the parts of the operator body that can come in contact in case of collision." | Khalid et al., 2017 |
| 153 | Hazards from control layer malfunction and misuse of collaborative system by attacker under a cyber-attack in a connected environment. | Khalid et al., 2017 |
| 154 | Operator dangerous location of working under heavy payload robot. | Khalid et al., 2017 |
| 155 | Time duration of collaboration in the process. | Khalid et al., 2017 |
| 156 | Hazards from end-effector and work part protrusions. | Khalid et al., 2017 |
| 157 | Physical obstacles in front of active sensors used in the collaborative workspace. (e.g. obstacle in front of camera). | Khalid et al., 2017 |
| 158 | Transition time from collaborative operation to other operation. | Khalid et al., 2017 |
| 159 | Non-provision of transition from collaborative operation to manual system in case of system malfunction. | Khalid et al., 2017 |
| 160 | Potential hazards from the industrial process (e.g., temperature, loose parts etc.) | Khalid et al., 2017 |
| 161 | Hazards from multiple workers involvment in the collaborative process. | Khalid et al., 2017 |
| 162 | Hazard created due to wrong perception of industrial process completion by the robot. | Khalid et al., 2017 |
| 163 | Hazard from trajectory taken by the robot. | Khalid et al., 2017 |
| 164 | Work material routing during the process. | Khalid et al., 2017 |
| 165 | Hazards from obstacles against unobstructed means of exiting the collaborative workspace at any instant. | Khalid et al., 2017 |
| 166 | Physical obstacles against robot operation during collaboration. | Khalid et al., 2017 |
| 167 | Physical obstacles tackled by worker in order to accomplish process requirement in collaborative workspace. | Khalid et al., 2017 |
| 168 | Hazard from visual obstruction for robot in collaborative workspace due to vantage point of operator. | Khalid et al., 2017 |
| 169 | Hazards due to task complexity in collaborative workspace. | Khalid et al., 2017 |
| 170 | Hazard from tight safety distance limit in the collaborative workspace. | Khalid et al., 2017 |
| 171 | "contact includes those hazards that can cause damage through direct contact, even if human, robot, or both are at rest (e.g., exposed electrical contacts). " | Kopp et al., 2021 |
| 172 | "exposure refers to all hazards that can occur from distance (e.g., vapors)" | Kopp et al., 2021 |
| 173 | "relates to the collision of human and robot. Hazards of this type are evaluated based on the kinetic energy defined in ISO/TS 15066:2016 [30]." | Kopp et al., 2021 |

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| # | Identified hazard or risk factor (as described by author) | Author |
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| 174 | "Also, it has been shown in other domains that objects within an operator's field of view that are salient but unrelated to the task at hand can capture the operator's attention, with potentially adverse consequences (Regan & Hallett, 2011; Wickens, Hollands, Banbury, & Parasuraman, 2013). Similarly, a fast-moving robot may disrupt completion of a task that is not related to the robot by capturing the operator's visual attention, leading to lower performance or elevated mental workload." | Koppenborg et al. 2017 |
| 175 | "Authors found:<br><br>- a higher level of speed leads to higher levels of risk cognition and anxiety.<br>- a higher level of speed leads to a higher level of mental workload, lower task performance, or both.<br>- levels of speed and predictability have interaction effects on risk cognition, anxiety, workload, and/or task performance." | Koppenborg et al. 2017 |
| 176 | "Because industrial robots can imply physical dangers to humans due to their power and size, operators may perceive working with a robot as risky and may react with anxiety (Kulic & Croft, 2007a, 2007b)." | Koppenborg et al. 2017 |
| 177 | "fatigue, monotony, and performance decrements While uncritical over a short duration, such effects can impair operator well-being and health when prevalent over a longer period. Safety is also degraded when these effects occur in critical situations that demand quick and precise action on the part of the operator." | Koppenborg et al. 2017 |
| 178 | "In this context, motion plans based on a quasi-static assumption quickly become obsolete, making reliance on replanning impractical — particularly if humans and robots are working in close proximity to one another, as there may not be sufficient time to replan. As a result, the ability to anticipate the actions and movements of members of a human-robot team is critically important for providing safety within dynamic HRI environments. Furthermore, this ability must extend to all team members, with both robots and humans able to predict one another's actions and motions." | Lasota, 2017 |
| 179 | "maintaining forces below thresholds for harm if there is collision" | Lasota, 2017 |
| 180 | "Pre-collision control methods are implemented before human-robot collision occurs, either by ensuring collision does not occur in the first place or by bounding robot pa- rameters such as velocity or energy. If unexpected or unpreventable contact occurs, post-collision control methods are designed to quickly detect the collision and minimize harm to both the human and robot. (Note that in this context, "collision" is not limited to blunt impacts, but can also include other harmful forms of contact, such as shearing, cutting, or puncturing.)" | Lasota, 2017 |
| 181 | "psychological safety is also of critical importance, as we discussed in Section 1.1. Maintaining psychological safety involves ensuring that the human perceives interaction with the robot as safe, and that interaction does not lead to any psychological discomfort or stress as a result of the robot's motion, appearance, embodiment, gaze, speech, posture, social conduct, or any other attribute. Results from prior experiments have indicated that maintaining physical safety by simply preventing collisions as they are about to occur can lead to to low levels of perceived safety and comfort among humans (Lasota and and Shah, 2015). Therefore, maintenance of physical safety alone cannot ensure safe HRI." | Lasota, 2017 |
| 182 | "While direct physical harm is prevented through careful programming, this type of interaction can be stressful for humans. Importantly, psychological discomfort or stress can also be induced by a robot's appearance, embodiment, gaze, speech, posture, and other attributes (Mumm and Mutlu, 2011; Butler and Agah, 2001) Stress can have serious negative effects on health (McEwen, 1993), which makes stressful HRI a potential source of harm. Furthermore, psychological discomfort caused by any of the other aforementioned factors, as well as robotic violation of social conventions and norms during interaction, can also have serious negative effects on humans over time. We define the prevention of this type of indirect, psychological harm as maintaining psychological safety.... not limited to proximal interaction, as it can also be sustained through distal interaction via a remote interface" | Lasota, 2017 |
| 183 | "engineering and human errors … errors in programming .. interfacing peripheral equipment could cause injuries to employees working with/around robots" | Leso, 2018 |
| 184 | "issues concern privacy invasion " | Leso, 2018 |
| 185 | "Main issues and concerns deriving from the applications of Industry 4.0 in workplaces: see fig 3 p 333 Psychological risk will be come more evident than physical ones" | Leso, 2018 |
| 186 | " issues concerns reduced inter-human contact" | Leso, 2018 |
| 187 | " issues concerns: risk of unemployment" | Leso, 2018 |
| 188 | "Combination of Mechanical design principles for the manipulator and simple control measures to supervise the safe operation of the robot to eliminate the risk of injury to the human operator due to the following main hazards:<br><br>Free impact between robot and operator, transient impact force to body part applies" | Matthias et all, 2011 |
| 189 | "Combination of Mechanical design principles for the manipulator and simple control measures to supervise the safe operation of the robot to eliminate the risk of injury to the human operator due to the following main hazards:<br><br>• Clamping configuration where robot applies holding force to body part static" | Matthias et all, 2011 |
| 190 | "Combination of Mechanical design principles for the manipulator and simple control measures to supervise the safe operation of the robot to eliminate the risk of injury to the human operator due to the following main hazards:<br><br>• Other application-specific hazards (introduced by tooling and work pieces used in application)" | Matthias et all, 2011 |
| 191 | "The results have shown that unpredictable robot motions have reduced the humans' well-being and performance and were not suited for HRI applications" | Michalos et al., 2015 |
| 192 | "Trust, workload and risk have been identified as the major human factors affecting the use of automation technologies. The human centered robotic cell design, according to [23], is mainly affected by human factors, such as workload, vigilance, situation awareness, errors etc. as well as by cognitive engineering related aspects and ergonomics. In [24] the influence of industrial robot motions in human-robot cooperative cells has been presented. The results have shown that unpredictable robot motions have reduced the humans' well-being and performance and were not suited for HRI applications" | Michalos et al., 2015 |
| 193 | "Trust, workload and risk have been identified as the major human factors affecting the use of automation technologies. The human centered robotic cell design, according to [23], is mainly affected by human factors, such as workload, vigilance, situation awareness, errors etc. as well as by cognitive engineering related aspects and ergonomics. In [24] the influence of industrial robot motions in human-robot cooperative cells has been presented. The results have shown that unpredictable robot motions have reduced the humans' well-being and performance and were not suited for HRI applications" | Michalos et al., 2015 |
| 194 | "Trust, workload and risk have been identified as the major human factors affecting the use of automation technologies. The human centered robotic cell design, according to [23], is mainly affected by human factors, such as workload, vigilance, situation awareness, errors etc. as well as by cognitive engineering related aspects and ergonomics. In [24] the influence of industrial robot motions in human-robot cooperative cells has been presented. The results have shown that unpredictable robot motions have reduced the humans' well-being and performance and were not suited for HRI applications" | Michalos et al., 2015 |
| 195 | "deducted from Safety Functions: Safety distance when bypassing human; Limited speed when bypassing human; Limited speed when approaching human; Signal when human approaches robot; Signal of good intentions when approaching human; Reaction to voice signals/commands from human; Reaction to gesture signals/commands from human; Wireless emergency stop" | Missala, Tadeusz 2014 |
| 196 | "Another cobot-related case of machine-human interaction creating new working conditions and OSH risks is when one person is assigned to 'look after' one machine and is sent notifications and status updates about machines on a personal device such as a smartphone or a home laptop. This can | Moore, 2019 |

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| | lead to risks of overwork, whereby workers feel compelled to take note of notifications in out-of-work hours and their work- life balance is disrupted (8)." | |
| 197 | "Data input problems, inaccuracies and faults with machine-to-machine systems create significant OSH risks as well as questions of liability. Indeed, sensors, software and connectivity can be faulty and unstable" | Moore, 2019 |
| 198 | "defining AI as "AI 'refers to systems that display intelligent behaviour by analysing their environment and taking actions — with some degree of autonomy — to achieve specific goals'"<br><br>OSH safety and health-related questions arising as AI is integrated into workplaces. Stress, discrimination, heightened precariousness, musculoskeletal disorders, and the possibilities of work intensification and job losses have already been shown to pose psychosocial risks, including physical violence in digitalised workplaces (Moore, 2018a). These OSH and the future of work: Benefits and risks of AI tools in workplaces risks are exacerbated when AI augments already existing technological tools or are newly introduced for workplace management and design. Indeed, AI exaggerates OSH risks in digitalised workplaces, because it can allow increased monitoring and tracking and thus may lead to micro- management, which a prime cause of stress and anxiety (Moore, 2018a). AI stresses the imperative of giving more credibility and potentially authority to what Agarwal and colleagues (2018) call 'prediction machines', robotics and algorithmic processes at work. But it is worth stressing that it is not technology in isolation that creates OSH benefits or risks. It is instead the implementation of technologies that creates negative or positive conditions." | Moore, 2019 |
| 199 | "OSH risks can further emerge because of a lack of communication, meaning that workers are not able to comprehend the complexity of the new technology quickly enough, particularly if they are also not trained to prepare for any hazards arising." | Moore, 2019 |
| 200 | "Potential OSH issues may also include psychosocial risk factors if people are driven to work at a cobot's pace (rather than the cobot working at a person's pace) and collisions between cobots and people (7)." | Moore, 2019 |
| 201 | "Risks of privacy relating to intensified surveillance and feelings of micro-management have been reported, as management is able to access more intimate data about workers because of wearable technologies in factories and offices alike." | Moore, 2019 |
| 202 | "three types of OSH risks in human-cobot-environment interactions (TNO, 2018, pp. 18-19):environmental risks, in which sensor degradation and unexpected human action in unstructured environments can lead to risks to the environment" | Moore, 2019 |
| 203 | "three types of OSH risks in human-cobot-environment interactions (TNO, 2018, pp. 18-19):robot-human collision risks, in which machine learning can lead to unpredictable robot behaviour;" | Moore, 2019 |
| 204 | "three types of OSH risks in human-cobot-environment interactions (TNO, 2018, pp. 18-19):security risks, in which robots' internet links can affect the integrity of software programming, leading to vulnerabilities in security;" | Moore, 2019 |
| 205 | "While this is good for the company's efficiency in production, lot size methods have led to significant OSH risks in that that they deskill workers, because skilled labour is needed only to design the on-the-spot training programmes used by those workers who no longer need to specialise themselves." | Moore, 2019 |
| 206 | "Changes of the musculoskeletal demands could lead to new ergonomics risks as back injuries due to material handling decrease while shoulder and wrist disorders may increase from the increase in computer workstation tasks. If the robots are poorly designed for maintenance access, then injuries to maintenance personnel may arise as they attempt to keep the cobot fleet operational." | Neumann, 2021 |
| 207 | "Focusing on outcomes of the task and impact on the workers, higher perceptual demands (in co-working with the cobot) could cause headaches or require additional tools to avoid this. Increasing cognitive and knowledge demands might influence work organization to allow for job rotation or additional training. " | Neumann, 2021 |
| 208 | "Implementing a cobot adds work to human order pickers for the identification of goods with damaged barcodes. Therefore, the worker has additional knowledge needs (1). As a result to this human impact, training should be offered to provide the necessary background for process handling (2). Training needs of course relate to initial learning effects that lead to a lower throughput at the beginning of the implementation and thus lower the system performance (3). Lower system performance and additional training needs lastly also have financial impacts for ramp up and training provision resulting from the added or removed piece of work (4)." | Neumann, 2021 |
| 209 | "Musculoskeletal disorders (MSDs), such as repetitive strain injuries, are a global problem caused by the design of work – particularly due to high forces, high duration and repetition of efforts, poor working postures, and poor psychosocial work environments (NRC, 2001). Population studies indicate that 20% of the general population suffers from" | Neumann, 2021 |
| 210 | "Rasmussen (1997) has pointed out that complex organisations engaged in process innovation and improvement will tend to "drift" to unsafe states. The rationale, supported by extensive analysis of organisational accidents, is that the efforts of many different actors working to minimise costs and optimize within their own limited domains will ultimately bring a complex system into an unstable state as they push the boundaries within their various domains in the pursuit of efficiency gains – leading to catastrophic systems failures (Rasmussen, 1997; Woo and Vicente, 2003; Burns and Vicente, 2000). If Rasmussen's assessment of dynamic organisations is correct – then the pursuit of I4.0 innovations is likely to follow this pattern as well: There will be unanticipated and unmanaged consequences emerging from the combined efforts of personnel in different parts of the system (Rasmussen) ...p8: "If HF is ignored, or dealt with in isolation, then underperforming systems and the ongoing problem of injured and killed workers can be expected." | Neumann, 2021 |
| 211 | "The absence of specific HF terms suggests, however, that this technology focused research rather pays lip service to humans but does not deal in any substantial way with human-system interaction, which causes the concerns that researchers are not paying attention to human aspects in their development work. When considered, then mental HF followed by physical HF have tended to be more common considerations, whereas psychosocial and perceptual aspects have been widely neglected, which manifests a clear lack of HF in I4.0 research. This suggests the I4.0 research is "blind" to the nature of the human system interactions in the systems they are helping to design.<br><br>The failure to address HF adequately in the design of work can lead to substantial problems. Current estimates from the International Labour Organisation place the annual work-related mortality at 2.78 Million deaths per year globally (ILO, 2019)." | Neumann, 2021 |
| 212 | "since robots may cause serious and fatal injuries to the human operators. In such cases, robot's speed is kept low to prevent harmful collisions." | Nikolakis, 2019 |
| 213 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to:<br><br>Business structures, hierarchies and relationships: Autonomous workers: the use of ICT-ET could enable flatter organisational structures with fewer middle- management posts (IFA, 2017). This could mean that workers have more autonomy over how they do their jobs (Mandl et al., 2015; Messenger et al., 2017) and in some cases also where and when. This could give workers more control over their workload and work patterns, thereby reducing work-related stress and improve workers' well-being (HSE, 2017). However, the loss of supervision by and support from middle management could also have a negative impact on OSH outcomes because, generally, middle managers have responsibilities for workloads, schedules, worker behaviour and well-being." | Stacey, 2018 |
| 214 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to:<br><br>Organisation and management of work: Cyber-security: the trend towards work processes and devices being controlled by and communicating with one another via the internet (or GPS technology, IoT systems, wireless networks, central databases, etc.) means that there is the potential for hackers to take control of them. This could compromise OSH" | Stacey, 2018 |
| 215 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: | Stacey, 2018 |

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| | Organisation and management of work: Digitalised management methods, including algorithmic management:… As a result, workers can lose control over work content, pace and scheduling, and the way they do their work (Moore, 2018). This is associated with work-related stress, poor health and well-being, lower productivity and increased sickness absence (HSE, 2017)." | |
| 216 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Organisation and management of work: Ethics of AI decision-making" | Stacey, 2018 |
| 217 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Organisation and management of work: The transparency and ethics of AI algorithms', machines' and robots' decisions will have an impact on workers' trust in and acceptance of such systems, as well as on workers' levels of stress and anxiety and other aspects of their mental health." | Stacey, 2018 |
| 218 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Organisation and management of work: Performance pressure: the use of ICT-ETs could cause a mismatch between workers' physical and/or cognitive capabilities and work demands. This could happen, for example, when working alongside collaborative robots, for AI bosses or with automated systems that have been designed to maximise the productivity benefits of such technologies without adequately considering the impact on human workers" | Stacey, 2018 |
| 219 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Organisation and management of work: Privacy invasion: ICT-ETs have the potential to invade workers' privacy in a number of different ways. Online platform workers, for example, may have to provide personal information without a clear guarantee of confidentiality (Mandl et al., 2015). ICT-ETs that are mobile, wearable and/or embedded in the bodies of workers could be used to constantly monitor them for a variety of reasons including productivity, appropriate behaviour, alertness and exposure to OSH risks. " | Stacey, 2018 |
| 220 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: 1. Malfunction caused by sabotage: if perception, understanding and trust in ICT-ETs are poor, workers may avoid using them or even act maliciously to try to confuse or defeat them, and sabotage will become more common. Workers' perception, understanding and trust will influence how they interact with ICT-ETs. Workers should be consulted and involved in strategies for deploying ICT-ETs in the workplace to ensure better OSH, as well as to increase acceptance and reduce sabotage." | Stacey, 2018 |
| 221 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: 2. Customisation: ICT-ETs often allow users to personalise them to a considerable extent. This can make them more user friendly for the person who has customised them, but less so for someone else. If a worker has to use a device customised by another, they may, for various reasons, not re-customise it. This could lead to stress, ergonomic-related harm or human error. Customisation culture could also lead to work equipment being used for a purpose for which it was not designed. The rapid reconfiguration of work processes in response to demands for and expectations about customisation from consumers may mean that the risk profile of a factory changes frequently. This could make it difficult to standardise procedures, risk assessments and other aspects of the management of OSH" | Stacey, 2018 |
| 222 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Control commands lost in transmission: human-machine interfaces, such as those based on gesture, voice, eye tracking or brain signals, could be misinterpreted by the work equipment or process under control" | Stacey, 2018 |
| 223 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Exposure to physical hazards. Safety risks will also be caused by the equipment that robots use, and which could pose dangers to workers in the vicinity. Examples include lasers, radiation sources, welding electrodes and mechanical equipment (Steijn et al., 2016). Little government guidance or policy exists regarding the safe integration of robots into the workplace and this is a new field for OSH professionals." | Stacey, 2018 |
| 224 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Lack of transparency of algorithms: a lack of transparency about how AI is analysing data and learning could lead to it behaving in unpredictable and unsafe ways. In the case of deep learning algorithms, for example, there is no way to identify which factors the deep learning program uses to reach its conclusion" | Stacey, 2018 |
| 225 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Mix of old and new: there is the potential for OSH risks during the transition from old to new technology when both are in service, particularly when the new needs to be integrated with the old and at the interfaces between the two. Infrastructure designed for old technology may not be suitable for new technology and could as a result introduce unforeseen OSH risks." | Stacey, 2018 |
| 226 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Pace of technological change: if the pace of change to work equipment is high, ICT-ETs may be replaced on failure rather than mended. This could reduce maintenance-related accidents. However, this could also increase the mix of technologies present in the workplace and create integration-related OSH issues. Pressure to bring a new design to market quickly, owing to consumer demand or competition, could increase the risk of design flaws not being found before work equipment is put into service, so that it could fail in unpredictable and hazardous ways. A high pace of technological change could cause mental health problems or exclusion from good-quality work for those unable to cope with constant change or 'newness' (sometimes referred to as 'technostress') (Suh and Lee, 2017). If workers' skills are unable to keep pace with change, this could have OSH consequences as a result of human error. " | Stacey, 2018 |
| 227 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Situational awareness: workers who use ICT-ETs to inform them about hazards could become less able to spot them on their own or check the information should the systems fail. This could lead to a decrease in situational awareness in general. A decrease in situational awareness can also arise when using VR devices, because of motion sickness and/or a loss of awareness of the user's actual surroundings during and even for some time after use (Hiesboeck, 2016). AR devices overlay reality with computer-generated information. The overlaid information could make it less easy to see OSH-critical situational information because of distraction, disorientation or information overload. However, AR could also improve situational awareness by providing supplementary contextual information" | Stacey, 2018 |
| 228 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Unforeseen situations: when designing robots, even if every effort is made to plan for all possible scenarios, it is impossible to foresee all situations. Ultimately, how safe it is depends on how the robot is used (it might be used incorrectly), and risks could be driven by | Stacey, 2018 |

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| | spontaneous and unforeseen actions by people, unexpected situations arising, software interacting with other software in ways previously unanticipated or a particular scenario arising that was simply not considered (Steijn et al., 2016). Incidents also — or especially — occur outside of normal operation, such as during the installation, testing or maintenance of robots. This underlines the importance of considering the entire life cycle of robots." | |
| 229 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Human-machine interaction and cognitive demands: real-time, interactive, direct and immersive human-machine interfaces could make it very difficult for workers to be able to pause or relax. If people work collaboratively with robots, they may be placed under pressure to perform at the speed of the robot. This could result in workers trying to meet very high efficiency demands placed on them by a robot that does not understand that humans cannot work at maximum efficiency all the time. ICT-ETs also enable some work processes to be automated such that some operators' roles will become supervisory, with only occasional intervention; operators are, therefore, likely to be required to oversee a number of work processes in several different locations, which could further increase cognitive demand. Intensive periods of continuous high cognitive demand placed on workers have the potential for negative impacts on OSH, particularly on mental health. Adaptive automation refers to the concept of software monitoring people who work with robots to adapt the speed of the process and prevent overloading (Steijn et al., 2016). This means that workers remain in control of the work process and workload, and it should also lead to greater acceptance of automation in the workplace." | Stacey, 2018 |
| 230 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Risk intensification: automation, while offering OSH benefits to many workers by removing them from exposure to hazardous environments, could also leave to workers only very repetitive tasks, with the robot determining the rate at which they are carried out, or the more difficult and/or dangerous tasks, and reduce the scope for task rotation and variety. For example, what is left could be a limited range of manual handling tasks requiring high dexterity, which could lead to an increased risk of repetitive strain injury. There is a trend towards the extreme specialisation of tasks, for example in warehousing, transport and distribution functions in the retail sector. " | Stacey, 2018 |
| 231 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Sedentary work: Sitting is the new smoking. A more sedentary lifestyle can increase the risk of poor postures, cardiovascular disease, obesity, stroke and diabetes " | Stacey, 2018 |
| 232 | "a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to: Work equipment and tools: Task deprivation: ICT-ETs enable work processes to be controlled, monitored and also increasingly maintained remotely. Jobs could, as a result, lose content and variety and become less satisfying. In addition, as equipment becomes smarter and more reliable, workers could be monitoring processes that rarely go wrong, resulting in boredom and loss of concentration (cognitive underload)" | Stacey, 2018 |
| 233 | "cyber-security risks due to an increase in the interconnectedness of things and people;" | Stacey, 2018 |
| 234 | "- the potential for automation to remove humans from hazardous environments, but also to introduce new risks, particularly influenced by the transparency of the underlying algorithms and by human- machine interfaces; ...- the algorithmic management of work and workers, AI, monitoring technologies, such as wearables, together with the Internet of Things and Big Data may lead to a loss of workers' control over their data, issues of data protection, ethical issues, information inequality with regard to OSH, and performance pressure on workers" | Stacey, 2018 |
| 235 | "workers lacking the necessary skills to be able to use ICT-ETs, cope with change and manage their work-life balance;" | Stacey, 2018 |
| 236 | "Employees must have a complete understanding of the robot, know how to deal with breakdowns, and know how to minimise the risk to themselves. Training, information, and adherence to internal procedures are essential aspects of this. P44: This entails people in organisations adhering to the relevant guidelines and taking any necessary training courses, and regularly updating them. It also means using appropriately qualified employees or organisations for composition, installation, configuration, maintenance, and disposal." | Steijn et al. 2016 |
| 237 | "exclude the possibility of maintenance employees running unnecessary risk." | Steijn et al. 2016 |
| 238 | "In order to create a safe robot, the entire supply chain involved with its life cycle is needed. The process starts by the supplier making a safe robot design. The system integrators then have to put the robot together, with safety as their first priority, and install it and configure it at the customer's premises, with the related certificate. The robot then has to be used safely, and systematically and safely maintained (including the software), and finally, kept up to date, also in a safe manner, or dismantled in the correct way and disposed of when it has become outdated. Responsibility for this is shared, in order to banish all the risk. Each party should carry out a risk inventory and risk evaluation responsibly (and be certified for doing so), but their responsibilities also extend beyond their own work activities. The supply provides instructions for the integrator, who trains the customer how to use the robot, and the customer gives feedback on how the robot is performing. Things have now reached the stage where industrial robots are controlled remotely, from India, for example. Operating jointly and keeping each of the other parties properly informed helps to optimise the process." | Steijn et al. 2016 |
| 239 | "Like people, robots depend on sensory information to be able to respond to their surroundings. However, it is easier for this information to be stored by robots. This makes robots a potential risk to privacy" | Steijn et al. 2016 |
| 240 | "One risk that has been mentioned is that robotisation means that robot software will soon determine what is and what is not possible. Take administrative robots, for example. They have great difficulty in dealing with exceptional circumstances that people have few problems handling, because they occur 'outside their software'. At the same time, organisations can quickly forget how a process takes place without the help of a robot. One example that was given was how, after a failure of the automatic check-in system at an airport, the changeover to a manual system proved very difficult." | Steijn et al. 2016 |
| 241 | "Potentially weak security of information and communication technologies (ICT) is a clear vulnerability, as a result of which the threat from hackers or loss of control have become real possibilities. Large robots in particular can be dangerous as soon as they can no longer be controlled of if someone else has taken over control of them. Robots can be connected directly or indirectly via these networks to public networks, including the internet. Because of malware, hacking, and technical and human errors, robots may behave differently in their physical environment to what is expected, as a result of which unsafe situations (for people) may arise. Eg.: Inaccurate sensor information; Disrupted communications between the sensors and the robot; A communications channel may be blocked; Disrupted communications between the robot and the 'home base'; Disrupted communications between robots themselves; Manipulated software or instructions; Unreliable control centre." | Steijn et al. 2016 |
| 242 | "Robots are very good at carrying out repetitive work accurately and quickly. People are creative, good at taking decisions, flexible, and adaptive. Using the best of both creates the best- possible benefit from the relationship between the two. If this is overlooked and employees become dependent on a robot, or if people no longer have any kind of challenge, there is a risk that they will not respond effectively in exceptional situations, or that the tasks that do remain are not challenging enough, thereby increasing the likelihood of errors being committed." | Steijn et al. 2016 |
| 243 | "robots should always have an emergency stop functionality. That is, people must always be able to switch off or overrule a robot in a safe manner. This means that people remain in control of, and responsible for, the entire process." | Steijn et al. 2016 |
| 244 | "Should a robot put a single employee in danger in order to maintain the overall safety of the plant?" | Steijn et al. 2016 |
| 245 | "Technological developments are moving fast and are not always easy to predict, which makes it difficult for the law and regulations to keep up. For example, there are currently no guidelines for self-driving machines, even though they are already on the market. An out-of-date standards framework could hinder the development of safety as a whole." | Steijn et al. 2016 |
| 246 | "the deployment of robots, the tasks that people carry out are changing. As a result of this change, employees' skills may get rusty because they are only used in emergencies. Cognitive underload and overload may occur leading to a greater likelihood of errors being committed, ...<br><br>p 36: Of course, this does raise the risk of a potentially mind-numbing task, in which the likelihood of distraction and error becomes greater" | Steijn et al. 2016 |
| 247 | "the deployment of robots, the tasks that people carry out are changing. As a result of this change,.... or they may suffer physical overload due to the tasks that remain being very repetitive, with the robot determining the rate at which they | Steijn et al. 2016 |

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| | p 36: Of course, this does raise the risk of a potentially mind-numbing task, in which the likelihood of distraction and error becomes greater | |
| 248 | "the risk of a collision between a person (torso, head, and limbs) and a robot" | Steijn et al. 2016 |
| 249 | "There is a risk of collisions when AGVs are started up incorrectly. An additional risk is the loss of a load during a collision. An example of a start-up risk is when an AGV's settings are not properly adjusted to the load it is to carry. For example, if the distance sensor is set to 120 mm, the AGV will not detect an employee if the forks are adjusted to 2 m. If an AGV fails to be logged in or out of a specific zone, it will not be registered by the overall system, creating a risk that it will not be detected. Another example is where an operator places another vehicle on the route of the AGV (deliberately or not)." | Steijn et al. 2016 |
| 250 | "Until now, most accidents involving robots have been related to the ignoring of safety zones or to the failure to observe safety instructions. Inefficient procedures or safety functions may have played a role here, as users look for ways to circumvent safety measures" | Steijn et al. 2016 |
| 251 | "Using a robot involves multiple parties - the developer of the robot, the system integrator, the installer, and the eventual user. A lack of clarity in where responsibility for safe use lies could lead to nobody taking it." | Steijn et al. 2016 |
| 252 | In general, people have a high level of trust in the capacities and functioning of machines and technology. However, these machines and the software that are used to operate them are themselves made by people and can therefore incorporate errors. " | Steijn et al. 2016 |
| 253 | "issues related to mental safety, intended as mental stress and anxiety induced by close interaction with robot, needs to be considered. This kind of information about the underlying psychophysiological condition of the operator during interaction can be exploited in a framework of affective robotics, which consists in enhancing the interaction of a human with a robot by recognizing her/his affect [77].Monitoring and interpreting nonverbal communication can provide important insights about a human inter- acting with the robot and, thus, implicit feedback about the interaction can be achieved. Accordingly, the aim of affective robotics is relieving userâs cognitive burden when the task to accomplish overloads her/his mental capabilities, adapting the behaviour of the robot and im- plementing a sufficient level of autonomy [78]. However, current ap- proaches based on affective robotics are mainly devoted to the field of socially interacting robots [77,79] and, to a lesser extent, service robots [80]; they are not yet common in industrial practice." | Villani et al, 2018 |
| 254 | "Monitoring and interpreting nonverbal communication can provide important insights about a human inter- acting with the robot and, thus, implicit feedback about the interaction can be achieved.(…) they are not yet common in industrial practice" | Villani et al, 2018 |

## Appendix D. Identified RFs (N=254) per class and subclass

| Technology (113 RFs) 44% | | | Human (68 RFs) 27% | | | Collaborative Workspace (36 RFs) 14% | | | Enterprise (34 RFs) 13% | | | External (3 RFs) 1% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subclass | Nr | % | Subclass | Nr | % | Subclass | Nr | % | Subclass | Nr | % | Subclass | Nr | % |
| Cobot system | 99 | 88% | Psychosocial factors | 37 | 54% | Physical design | 33 | 92% | Ethics | 12 | 35% | Environmental conditions | 2 | 67% |
| Operating system | 14 | 12% | Cognitive ergonomics | 19 | 28% | Maintenance | 3 | 8% | Organizational ergonomics | 12 | 35% | Regulatory | 1 | 33% |
| | | | Physical ergonomics | 12 | 18% | | | | Technology strategy | 8 | 24% | | | |
| | | | | | | | | | Safety strategy | 2 | 6% | | | |

## Appendix E. Illustration of selected subclass topics (non-exhaustive) as extracted from RF identification list

| Illustration of some subclass topics (non-exhaustive) | CLASS | SUBCLASS | Risk factor as described by author | authors | source ref | page ref |
|---|---|---|---|---|---|---|
| WORKSTRESS | Human | Psychosocial factors | The role of ergonomics in HRI should be to support humans in the reduction of work-related biomechanical and cognitive overload without introducing new hazards for the health and safety of the operators (e.g. **work-related stress** which potentially could arise from the interaction with the robot systems). | Gualtieri, 2021 | M85 | 23 |
| | Human | Psychosocial factors | (ii) indirect or psychological injuries caused by many factors such as robot appearance, embodiment, gaze, speech, posture [134,315]. | Hentout et al. 2019 | WoS47 | 774 |
| | Human | Psychosocial factors | possible **stress,** fatigue, or lack of concentration arising from the collaborative operation; | ISO15066 | M88 | 3-4 |
| | Human | Psychosocial factors | Consider, for example, a hypothetical manufacturing scenario in which a robot uses a sharp cutting implement to perform a task in proximity to human workers, but is programmed to stop if a human gets too close. While direct physical harm is prevented through careful programming, this type of interaction can be **stressful for humans.** Importantly, **psychological discomfort or stress** can also be induced by a robot's appearance, embodiment, gaze, speech, posture, and other attributes (Mumm and Mutlu, 2011; Butler and Agah, 2001) Stress can have serious negative effects on health (McEwen, 1993), **which makes stressful HRI a potential source of harm**. | Lasota, 2017 | M81 | 263 |
| | Human | Psychosocial factors | issues related to **mental safety,** intended as **mental stress and anxiety induced by close interaction with robot,** needs to be considered. This kind of information about the underlying psychophysiological condition of the operator during interaction can be exploited in a framework of affective robotics, which consists in | Villani et al, 2018 | WoS95 | 256 |

(*continued on next page*)

(*continued*)

| Illustration of some subclass topics (non-exhaustive) | CLASS | SUBCLASS | Risk factor as described by author | authors | source ref | page ref |
|---|---|---|---|---|---|---|
| | | | enhancing the interaction of a human with a robot by recognizing her/his affect [77]. | | | |
| SECURITY | Technology | Operating system | **Cybersecurity** is the process of protecting information by preventing, detecting, and responding to attacks [58]. As technology grows, robots are increasingly connected to the network, constantly exchanging information [61]. This makes robots exposed to cyber attacks that can lead to data leakage, malfunction, or even damage to peo- ple or property. For | Gervasi, 2020 | M79 | 853 |
| | Technology | Operating system | As more and more IT-related operations are transferred to the “cloud”, operator safety increasingly also means the same thing as IT security | Grahn et al. 2017 | M9 | 119 |
| | Technology | Operating system | Functions for robot control are increasingly moving to the “cloud”, this means that lacking IT-security also directly results in operator safety hazards | Grahn et al. 2017 | M9 | 113 |
| | Technology | Operating system | **cyber-security** risks due to an increase in the interconnectedness of things and people; | Stacey, 2018 | M100 | 7 |
| | Technology | Operating system | Potentially **weak security of information and communication technologies (ICT)** is a clear vulnerability, as a result of which the threat from hackers or loss of control have become real possibilities. Large robots in particular can be dangerous as soon as they can no longer be controlled of if someone else has taken over control of them. Robots can be connected directly or indirectly via these networks to public networks, including the internet. Because of malware, hacking, and technical and human errors, robots may behave differently in their physical environment to what is expected, as a result of which unsafe situations (for people) may arise.<br>Eg<br>.: Inaccurate sensor information; Disrupted communications between the sensors and the robot; A communications channel may be blocked; Disrupted communications between the robot and the ‘home base’; Disrupted communications between robots themselves; Manipulated software or instructions; Unreliable control centre. | Steijn et al. 2016 | M24 | 19-20 & 27 |
| SOFTWARE | Technology | Cobot system | Additionally to the intrinsic decisional difficulty, it is also important to mention the residual faults **(bugs)** in the software as another source of hazard. | Guiochet et al. 2017 | M11 | 7 |
| | Technology | Cobot system | **Risks of software components can also be caused by uncertain factors in the working environment** to which the robot is exposed (e.g. sensor degradation, unexpected human action, **use of the robot in unstructured environments** such as building sites or newly configured production lines). | Jansen, et al. 2018 | M80 | 18 |
| | Technology | Cobot system | “**risks due to robots becoming more intelligent as a result of Artificial Intelligence built into the software**”. “When implementing cobots in the workplace it is important to ascertain what capabilities they need in order to be able to interact safely with humans. An important point is that cognitive cobots display real-time, adaptive, anticipatory behaviour based on an observed situation and future circumstances (based on past experience). As regards AI, there is a difference between **symbolic AI** (usually logic-based, with explicit knowledge representations, enabling a human-robot shared mental model and situation awareness) and **sub-symbolic AI (machine learnin**g, which is more of a black box for the user). As regards machine learning, an important point is whether it is applied at design time or at run-time.”. “**machine learning can result in unpredictable behaviour on the part of the robot.**”<br><br>“ **Machine learning can create risks particularly if the current situation differs from the situation in which the learning originally took place** (the learned model is not applicable to the current situation). Incorrect perception of the environment, or inappropriate response to unplanned situations faced by the robot, and erroneous reasoning by the robot or errors in the knowledge representation of the system in which the robot moves around, can cause incidents.”<br>Further explained ao applied to AGV’s: p 41 - 42 | Jansen, et al. 2018 | M80 | 5, 14, 17 |
| | Technology | Cobot system | engineering and human errors … **errors in programming** .. interfacing peripheral equipment could cause injuries to employees working with/around robots (citing Vasic) | Leso, 2018 | WoS98 | 334 |
| ACCESS & CLEARANCE | Collaborative Workspace | Physical design | Physical fences requires deliberate actions and does **not allow for easy entry** to a hazardous space, thereby mitigating risks associated with automation misuse. | Gopinath, 2019 | WoS57 | 6 |
| | Collaborative Workspace | Physical design | Physical fences requires deliberate actions and does **not allow for easy entry** to a hazardous space, thereby mitigating risks associated with automation misuse. | Gopinath, 2019 | WoS57 | 6 |

(*continued on next page*)

(*continued*)

| Illustration of some subclass topics (non-exhaustive) | CLASS | SUBCLASS | Risk factor as described by author | authors | source ref | page ref |
|---|---|---|---|---|---|---|
| | Collaborative Workspace | Physical design | **accessibility** for operators; | ISO15066 | M88 | 3-4 |
| | Collaborative Workspace | Physical design | **identification** of persons (groups) with access to the collaborative robot system; | ISO15066 | M88 | 3-4 |
| PRIVACY | Enterprise | Ethics | issues concerns **privacy invasion** | Leso, 2018 | WoS98 | 335 |
| | Enterprise | Ethics | Risks of **privacy** relating to intensified surveillance and feelings of micro-management have been reported, as management is able to access more intimate data about workers because of wearable technologies in factories and offices alike. | Moore, 2019 | M92 | 15 |
| | Enterprise | Ethics | a number of OSH challenges and opportunities that may emerge as ICT-ETs change to be identified; these relate to:<br><br>Organisation and management of work**: Privacy invasio**n: ICT-ETs have the potential to invade workers' privacy in a number of different ways. Online platform workers, for example, may have to provide personal information without a clear guarantee of confidentiality (Mandl et al., 2015). ICT-ETs that are mobile, wearable and/or embedded in the bodies of workers could be used to constantly monitor them for a variety of reasons including productivity, appropriate behaviour, alertness and exposure to OSH risks. | Stacey, 2018 | M100 | 56 |
| | Enterprise | Ethics | Like people, robots depend on sensory information to be able to respond to their surroundings. However, it is easier for this information to be stored by robots. This makes **robots a potential risk to privacy** | Steijn et al. 2016 | M24 | 22 |

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