EMERGENT RISKS TO WORKPLACE SAFETY; WORKING IN THE SAME SPACE AS A COBOT

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innovation for life

Report for
Ministry of Social Affairs and Employment

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Foreword

This report on ‘Emergent risks to workplace safety; working in the same space as a cobot is the third in the series of reports on emergent risks in relation to new technologies.

The 2016 report on ‘Emergent risks to workplace safety as a result of IT connections of and between work equipment’ examined the relationship between IT connections and protection against cyber security risks. The report on ‘Emergent risk to workplace safety as a result of the use of robots in the work place’ was issued last year: this examined how to control workplace safety risks during the various phases of the robot life cycle.

In the present report TNO builds on this knowledge by identifying the workplace safety risks and appropriate control measures in relation to emergent autonomous systems that employees will be collaborating with in the future, referred to as ‘cobots’. The end-result is a Safety Chart showing a number of important risks and risk control measures. The Safety Chart is a practical tool for businesses, employers and employees showing how to organize a safe, healthy workplace when using cobots. It also provides an important source of information for follow-up studies.

TNO would like to thank the participating companies and authorities for their contribution to knowledge development in the area of robotics and workplace safety. TNO wishes readers success with implementing the knowledge that has been developed and inspiration to control new risks in the workplace.

Contents

Glossary of Abbreviations

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AR	Augmented Reality
CES	Company Emergency Services
CE	Conformité Européenne
CHTRA	Cobot-Human Task Risk Analysis
FA	First AID
FTA	Fault Tree Analysis
FMECA	Fail Mode, Effects and Criticality Analysis
HAZOP	Hazard and Operability study
HR	Human Resources
HSE	Health, Safety & Environment
ISO	International Organization for Standardization
LED	Light-Emitting Diode
LiDaR	Light Detection And Ranging
LMRA	Last Minute Risk Assessment
LORA	Levels of Robot Autonomy
MAR	Multi-Annual Roadmap for Robotics
MBO	Middelbaar Beroepsonderwijs (senior secondary vocational education)
HRI	Human-Robot Interaction
MSAE	Ministry of Social Affairs and Employment
PHA	Process Hazard Analysis
PL	Performance Level
PLC	Programmable Logic Controller
PWF	Psychosocial Work Factor(s)
RI&E	Risk Identification & Evaluation
SIL	Safety Integrity Level
SLAM	Simultaneous Localization and Mapping
TRA	Task Risk Analysis

1 Introduction

In 2015 the Ministry of Social Affairs and Employment (subsequently referred to as the MSAE) asked TNO to carry out research into the emergent risks to workplace safety as a result of removing the physical barriers around machines and robots in industrial working environments. In 2016 this resulted in a research report and a concise summary of the risks and control measures, which were then set out in accordance with health and safety strategy in a 'Safety Chart ', taking account of the various phases in the robot life cycle. As a follow-up to that report this study specifically looks at the workplace safety risks and appropriate control measures in relation to cobots.
The 2015 report used examples to show that the robot industry is advancing with great rapidity in various sectors (from healthcare to manufacturing). A direct result is that robots will increasingly be taking over work from humans and/or supporting it. The programming of industrial robots is also becoming increasingly complex, and robots are increasingly carrying out more – or more complex – tasks autonomously to a greater or lesser extent. 'Autonomously' in this context means that they are programmed to be able to take decisions for themselves (using AI). These robots can 'see' their environment using sensors and anticipate it and respond to it. They are self-learning and can move in space independently. In the near future they will no longer be restricted to a fixed location or cage but will share the workplace with their human colleagues.

These robots are referred to as 'collaborative robots' ('cobots' for short). A good example is ABB's small robot YuMi, which is already uncaged, although it stands on a pedestal. YuMi is self-learning, communicates with a service centre using Industry 4.0 standards, works together with an assembly worker and stops if anyone touches it. The next step towards 'collaborative workspace' would seem to be imminent: this is a shared task environment in the workspace, where the robot system (including the workpiece) and a human can perform tasks at the same time as part of the production process.

A standard on these collaborative robots (ISO TS 15066) was published by ISO almost simultaneously with the TNO report. Later on in this report we shall consider this new standard in more detail (§3.1), but for the time being it is important in particular to note that even this standard has not been able to cover all the possible risks that the introduction of new technologies can entail. Take, for example, cyber security threats to cobots (see the 2015 TNO report), or risks due to robots becoming more intelligent as a result of Artificial Intelligence built into the software. Further exploration of the possible risks and appropriate control measures is therefore still needed to support future developments of the standard and legislation on cobots.

The use of self-learning algorithms in the software, combined with cobots' increased mobility and decision-making autonomy, could eventually make their actions less predictable for the human operators who need to collaborate with them. The primary risk reduction strategy used for traditional robot systems – the use of technical safeguards that segregate the robot from humans and thus remove the hazard – is no longer applicable to collaborative human-robot systems, as shielding cobots would take away their added value. The physical cage therefore needs to be replaced with a reliable, robust virtual cage (referred to as a 'soft cage') to guarantee the safety of their human colleagues.

For a design to be inherently safe it needs to anticipate possible (foreseen) risk scenarios due to cobot behaviour, but no design can ever foresee everything. It is therefore important to see cobots as participants in the bigger human-environment picture. A cobot operates in a 'cobot-human-environment system', in which the cobot and the human work together as a team, as it were, each with their own tasks and responsibilities, which require coordination and communication.

In this report TNO takes a first step by identifying the workplace safety risks and appropriate control measures in relation to cobots, focusing particularly on the workplace safety risk of injury or death as a result of an incident involving one or more humans and a cobot in the workplace. In support of this aim, the following requests for information were made for this report:

1: What cobot systems with a degree of autonomy are already available or expected in the near future?

2: What are the expected or already manifest effects of these systems on actual – workplace and process – safety risks such as those that occur in industrial environments, and what control measures are there?

3: To what extent are existing techniques for analysing and controlling risks usable in work situations where more autonomous robot systems are deployed, or are additional approaches needed?

1.1 Results of research

Based on the requests for information set out on the previous page, this report delivers the following results:

Research question 1: an overview of applications of AGVs and cobots with a high degree of autonomy (in warehouses) and potential risks.

Research question 2: an overview of risks and risk control measures relating to automated robot systems.

Research question 3: a model that will make model-based risk identification and analysis of human-robot software systems possible in the future.

1.2 Organization of the report

The report sets out a description of the methodology used to answer the research questions and the resulting overview of risks and possible control measures. Chapter 2 explains the methodology adopted, namely a literature survey, interviews and a workshop. Chapter 3 sets out the results of the literature survey and the workshops. Chapter 4 presents a summary of the results of the interviews and the workshop. Lastly, Chapter 5 draws general conclusions on the research questions, and contains a brief discussion looking at the future and making recommendations.

2 Approach

The following activities were carried out in order to answer the research questions and enable the expected results to be delivered.

1. **Literature and internet scan:** A literature and internet scan was carried out to explore the topic and delineate the scope of this report (see Chapter 3). A framework for human-robot-environment interaction was also drawn up to enable relevant hazards and control measures to be identified and categorized. The literature and internet scan primarily answered Requests for Information 1 and 3.
2. **Structured interviews:** Structured interviews were held with experts in the field of cobot safety, cobot development and cobot use. These focused particularly on answering Research question 2.
3. **Workshop session:** We held a workshop at which we fed back the initial results from steps 1 and 2 to the experts interviewed in order to obtain additional information and explore the subject in greater depth. Here again we focused particularly on obtaining further information in answer to Research question 2.

Health and safety strategy
Based on the earlier TNO reports, the health and safety strategy will be used as the basis for the risk control results obtained from the interviews and the workshop. It contains the following hierarchy of control measures as set out in the Health and Safety at Work Act (*Arbowet*):

1. Measures at source (e.g. eliminating and isolating hazard).
2. Collective measures (e.g. shielding a group from hazard).
3. Individual measures.
4. Personal protective equipment.

The strategy sets out the sequence in which organizations should adopt safety measures, based on the best available techniques. It is also based on the reasonableness principle, which states that measures can be adopted at a different level if measures at a higher level are not feasible within reason or are only partly feasible.
The control measures adopted must be effective in practice. Any indication of the degree of effectiveness will depend on the circumstances that they are designed to deal with. The feasibility of the measures adopted will depend on such things as requirements under standards, the conditions in which employees work, or situations in which measures are mutually exclusive (if one measure is adopted the other measure will have no added value).

Life cycle
This project approaches the new risks and risk control measures in terms of the life cycle of work equipment. This breaks down into (a) design/engineering, (b) production/integrators/delivery/installation, (c) use, (d) maintenance, (e) replacement and (f) disposal.

Similar phases can be identified in the entire life cycle of cobots. The use and maintenance phases are important, as in these phases the safety risks in relation to humans in the work process mainly manifest themselves and can be studied.

2.1 Literature and internet scan

In order to explore the area of research (human-robot interaction and workplace safety), and in preparation for the research questions, we carried out a literature survey to look for sources of information, which provided theoretical information in answer to Research question 2. The following aspects are discussed in §3.1:

1. Definitions of collaborative robots and examples in the logistics chain.
2. Robot autonomy and human-cobot collaboration.
3. Cobots' symbolic (semantic knowledge) and sub-symbolic AI (machine learning).
4. Factors involved in social interaction with humans.

For Research question2 we went on to look at existing guidelines on the safe design of cobots to protect against physical hazards and general risks involved in the use of cobots in an industrial setting.
In order to answer Research question3, we looked at literature describing recent risk analysis techniques capable of identifying the risks of, and risk control measures for, cobots.

2.2 Interviews

2.2.1 Interview protocol

The interviews were semi-structured, i.e. based on a predetermined protocol containing questions that could serve as a guide. The main purpose of the interviews, however, was to interrogate the interviewees on subjects on which they could provide a lot of information. Each interview lasted between an hour and one-and-a-half hours. The interview protocol can be found in Appendix A. Questions were adapted to the interviewee's background where necessary.

2.2.2 Participants

Based on the literature and internet scan an actor analysis was carried out, mainly selecting actors with knowledge of robot systems in general and actors with specific knowledge of AGVs. These experts were then e-mailed to invite them to an interview. The target was a maximum of eight participants. The first series of invitations were sent out in August. Table 1 gives brief descriptions of the interviewees (anonymized).

Table 1: Backgrounds of interviewees

Post	Specialism
1 Producer	Automated mobile vehicles + cobots
2 Researcher	Safety engineering in the automotive industry
3 Producer and systems integrator	AGVs, cobots and modular systems
4 Producer	Two-armed cobots
5 Systems integrator	AGVs and cobots
6 Producer and systems integrator	Robot arms
7 End-user	Food industry safety
8 End-user	Food industry safety

2.3 Workshop

A workshop on '*Working together safely with cobots*' was held in October.
Experts were invited to attend this workshop at the end of the interview. Invitations were also sent out to the same list of actors used to compile the list of interviewees, ultimately resulting in 14 participants and three TNO project members. The 14 participants included four previous interviewees. Table 2 gives an overview of the participants.

The aim of the workshop was to answer Research question 2 by comparing three specific systems (a traditional vehicle, the current AGV and the AGV of the future). The threats (hazards), vulnerabilities and control measures were examined for each type. This involved dividing the participants into two groups, who brainstormed in two parallel sessions on risks and control measures using two bow-tie diagrams. These diagrams contained a number of pre-defined threats and consequences; others could be added by the groups. After forty minutes the groups exchanged topics for a second round.

One of the bow-ties was based on a fictitious central event that created distrust of the automated autonomous cobot. The other bow-tie was based on a central event in which there was a collision with a human. The two groups developed the two scenarios independently.

The workshop concluded by comparing and combining the results of the workshop and then drawing conclusions on the expected safety and health effects of AGVs in the future. Chapter 4, Interview and workshop results, sets out the threats, consequences and control measures in greater detail. No bow-ties were developed for the 'traditional machine' (fork-lift truck) because the candidates did not have enough knowledge of such machines. The findings on this topic were therefore compiled after the workshop, based on fact sheets from the National Institute for Public Health and the Environment (RIVM).

Table 2: Workshop participants

Organization	Type
1 TNO	Research institute
2 FANUC	Producer
3 Van der Lande	Systems integrator
4 AGV International	Systems integrator
5 SICK	Producer
6 Robomotive	Systems integrator
7 Probotics (Fontys University of Applied Sciences)	Knowledge Institution/Producer and Systems Integrator
8 Holland Robotics	Robotics platform
9 Philips Consumer Lifestyle	Producer
10 Heemskerk Innovative Technology	Consultancy
11 FMI Industrial Automation BV	Producer
12 Royal Ahold Delhaize	End-user

3 Results of literature survey of cobots

The literature survey primarily answered the following requests for information:

Research question 1: What cobot systems with a degree of autonomy are already available or expected in the near future?

Research question 3: To what extent are existing techniques for analysing and controlling risks usable in work situations where more autonomous systems are deployed?

In addition, the literature survey provided information (in §3.2) on design constraints for cobots that partly answers Research question 2. That section also makes a start on identifying the risks of and control measures for cobots, which are developed in Chapter 4 on the results of the interviews and workshop.

3.1 Research question 1

This section provides information in response to Research question 1:

What cobot systems with a degree of autonomy are already available or expected in the near future?

To answer this question we first need a description and definition of cobots and their characteristics.

3.1.1 Definitions of collaborative robots

Definition of robot:[1] '*A robot is a machine that can be programmed, has sensors and has a certain degree of mobility enabling it to perform a task autonomously (independently).'*

Another interesting definition of a robot which can be added here relates to autonomous observation and action, which makes it interesting in relation to this study: '*A robot is a physical agent (machine) that can perceive its environment through sensors and (semi-autonomously) act upon that environment through actuators*'.[2]

If there is interaction between a human and a robot, this can take place at three levels: coexistence, cooperation and collaboration (see Fig. 1). Collaborative robots (cobots) have the greatest capacity for human-robot interaction. In the case of coexistence the interaction is confined to the fact that the robot and the human perform tasks at the same time in the same working environment.[3] In the case of cooperative robots and cobots the human and the robot also have a common aim.

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[1] TNO 2016 R10643 Emergent risk to workplace safety as a result of the use of robots in the work place.
[2] http://dai.fmph.uniba.sk/courses/intro-ai/reading/3ed-ch02-agents.pdf
[3] Bortot, Dino. *Ergonomic human-robot coexistence in the branch of production.* Verlag Dr. Hut, 2014.

Lastly, in the case of cobots there is the possibility of physical contact between the human and the robot in a shared space. This above all is what distinguishes cobots from other systems.

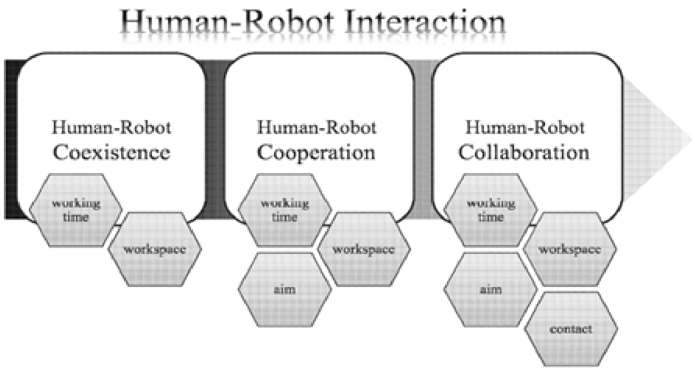

Figure 1: Types of human-robot interaction: Coexistence, Cooperation and Collaboration (cobots).

Definition of cobot:[4] A cobot or co-robot (from 'collaborative robot') is a robot designed to be able to have physical interaction with humans in a shared working environment – unlike other robots, which are designed to work independently, with limited interaction with humans.
N.B. The researchers point out here that physical interaction involves intervening in the same shared environment (co-location) together with humans, using actuators (see the definition of a robot).

The shared workspace is a zone within the user's workspace where the robot system and the user (with the workpiece) can perform tasks at the same time during the work process.[5] Employees can thus work in the vicinity of a cobot while it is operating, and direct (physical, haptic or auditory) contact can take place between an employee and the cobot.[6] Indirect physical contact can also take place, however, as collaboration always involves interdependence (see Johnson et al., 2014). If the cobot knocks something over, for example, this can have consequences for the human, and vice versa. In this respect it is important to secure the working environment in order to achieve safe interaction.

Although the MAR (Multi-Annual Roadmap for Robotics)[7] does not make this distinction, there is always a difference in complexity when collaborating with cobots, depending on the tasks being performed.
The Universal Robotics[8] white paper 'The Role of Cobots in Industry' lists a number of characteristics of cobots to give a better idea of what they are.

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[4] https://en.wikipedia.org/wiki/Cobot
[5] ISO TS15066 (2016) Robots and robotic devices – Collaborative robots
[6] ISO TS15066 (2016) Robots and robotic devices – Collaborative robots
Robots et dispositifs robotiques – Robots coopératifs
[7] Robotics 2020: Multi-Annual Roadmap For Robotics in Europe, Horizon 2020 Call ICT-2017 (ICT-25, ICT-27 & ICT-28), 2017
[8] Ostergaard, The Role of Cobots in Industry 4.0, Universal Robotics

Cobots:

- have robot arms.
- work together with humans in a non-shielded environment.
- can be easily programmed by the user.
- serve as a tool (not a replacement) for employees.
- help companies to control their automated processes.

A ‘warehouse cobot’ is a robot system that is able to work safely, autonomously and in physical collaboration with human employees to fetch and/or move items in a warehouse, to store them and to help with the packing and unpacking of storage units. It is able to carry, select, pack or process objects. The system has the following properties:

- Human-robot interaction that adapts to a changing environment and workload (without substantial restructuring of the warehouse).
- Easy configuration security.
- Ability to contact other warehouse systems via an interface and to add or link to a warehouse planning system, optimization algorithms, stock control software, etc. (MAR, 2017).[9]

The difference between a cobot and a cooperative robot is that a cooperative robot has no direct contact with humans:[10] *Two agents are in a cooperative situation if they meet two minimal conditions:*
(1) Each one strives towards goals and can interfere with the other on goals, resources, procedures, etc.
(2) Each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists.
Hoc (2001)[11] defines a cooperative situation mainly in terms of the degree to which the robot provides assistance to humans.

Definition of Automated Guided Vehicle (AGV): *‘An Automated Guided Vehicle is a mobile robot that follows markings, lines, magnets or lasers in the workplace in order to move from A to B*.’[12]

Although not completely in line with this definition, there are recent developments in automated guidance involving the use of cameras to create an image of the environment (also using e.g. markings in the environment to determine position and navigate).

Based on the above classification (Fig. 1), an AGV can be regarded as a robot that is cooperative or merely co-existing; it is not therefore covered by the definition of a cobot. Some companies, however, (e.g. Tesla) have AGVs in operation that do collaborate with

[9] Robotics 2020: Multi-Annual Roadmap For Robotics in Europe, Horizon 2020 Call ICT-2017 (ICT-25, ICT-27 & ICT-28), 2017
[10] J. Schmidtler et al. (2015) Human Centred Assistance Applications for the working environment of the future.
[11] Hoc, J.-M. (2007). Human and automation: a matter of cooperation. HUMAN 07, Timimoun: Algeria.
[12] https://en.wikipedia.org/wiki/Automated_guided_vehicle

humans: these take the 'battery' from a rack and place it in the car from below, while the employee fits the part.
AGVs are an important part of the current state of robot technology in internal logistics, and therefore provide an important area for this study to explore interactive safety when using cobots in internal logistics. While the results cannot be applied one-on-one to cobots, they do provide insights that may contribute to the understanding of the interactive safety of cobots in logistics or production processes.

Appendix B sets out the results of a survey of cobots and AGVs in internal logistics and describes their applications. Table 3 gives an overview of the systems identified.

Table 3: List of robot systems identified

Cobot	Applications	AGV	Applications
Parcel Robot	Loading and unloading	Forklift and clamp AGV	Loading and unloading, storage and transport
DHL Robot	Loading and unloading	Narrow-aisle trucks	Storage and transport
SSI Schaefer Robo-Pick	Order-picking		
KIVA	Order-picking		
TORU	Order-picking	Automated mobile transport vehicles	
Baxter	Packing	Tractor AGV	Transport
YuMi	Packing	Transfer AGV	Transport and order-picking

3.1.2 Robot autonomy and human-cobot collaboration

Autonomy is a relative term, which is always defined in relation to the characteristics of the environment[13] or 'user'. As in the case of systems-of-systems, autonomy can be defined at various levels of abstraction simultaneously. Autonomy is a 'state-of-being' that requires a certain degree of robustness in relation to the environment, independence of action or function, and self-determination of goals and source allocation.[14]

A typical feature is that autonomous/semi-autonomous robots have more freedom of movement, making their behaviour more difficult for the outside world to control. A robot's speed of action also affects the potential for intervention. Human trust in robots is thus an important aspect of collaboration, based on image-building and experience.[15,16,17] Too much

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[13] Bradshaw, J.M., Feltovich, P.J., Jung, H., Kulkarni, S., Taysom, W., & Uszok, A. (2004). Dimensions of adjustable autonomy and mixed-initiative interaction. In M. Klusch & G. Weiss (Eds.), Agents and Computational Autonomy (Vol. 2969, pp. 17–39). Berlin/Heidelberg: Springer.
[14] Kaber, D.B. (2017). Issues in human-automation interaction modeling: Presumptive aspects of frameworks of types and levels of automation. *Journal of Cognitive Engineering and Decision Making, 1555343417737203.*
[15] Schaefer, K.E., Billings, D.R., Szalma, J.L., Adams, J.K., Sanders, T.L., Chen, J.Y., & Hancock, P.A. (2014). A meta-analysis of factors influencing the development of trust in automation: Implications for human-robot interaction (No. ARL-TR-6984). Army Research Lab Aberdeen Proving Ground MD Human Research and Engineering Directorate.
[16] Salem, M., Lakatos, G., Amirabdollahian, F., & Dautenhahn, K. (2015, March). Would you trust a (faulty) robot?: Effects of error, task type and personality on human-robot cooperation and trust.

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.

If a cobot is to have a certain degree of autonomy, it is important to take the robot's programmed capabilities into account, since the extent to which it operates autonomously is determined partly by the extent to which it is able to perceive the environment and plan and act on that environment, with little or no external control.[18]

A robot can only operate truly autonomously once it has all the capabilities required to carry out an activity safely in a particular environment in relation to its tasks.[19] In theory, the greater a robot's capability, the more autonomously it needs to be able to move and act in relation to its tasks.

Human-cobot interaction is based on optimum use of the capabilities of both the human and the cobot, and the corresponding division between autonomy and dependence (or collaboration). Autonomy thus applies to subtasks; it is never complete. In this case there is interdependence, which is defined as follows:

'Interdependence' describes the set of complementary relationships that two or more parties rely on to manage required (hard) or opportunistic (soft) dependencies in joint activity (Johnson et al., 2014).

Almost all robot systems have a certain degree of autonomy, ranging from a simple movement that the robot can stop as a result of sensory perception to the ability to be self-controlling in a complex working environment. Beer et al. (2012) have developed a multidimensional model of autonomy, which they relate to the task and human-robot interaction aspects. It defines ten levels of robot autonomy, from manual to fully autonomous (LORA). The extent to which a cobot is able to perceive, plan or act differs from one task to another. The extent to which it is able to carry out a task safely and independently based on observation, planning or action is indicative of the degree of robot autonomy in human-robot interaction and depends partly on its capabilities and the working environment.

3.1.3 Symbolic and sub-symbolic AI

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

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In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction (pp. 141-148). ACM.

[17] De Visser, E.J., Pak, R., & Neerincx, M.A. (2017, March). Trust Development and Repair in Human-Robot Teams. In Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction (pp. 103-104). ACM.

[18] Beer, J.M., Fisk. A.D., & Rogers, W.A. (2012). Toward a psychological framework for levels of robot autonomy in human-robot interaction. Technical Report HFA-TR-1204, Georgia Institute of Technology. https://smartech.gatech.edu.

[19] Johnson, M., Bradshaw, J.M., Feltovich, P.J., Van Riemsdijk, M.B., Jonker, C.M., & Sierhuis, M. (2014). Coactive design: Designing support for interdependence in joint activity. Journal of Human-Robot Interaction, 3 (1), 2014.

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.

In physical interaction with the operator in a more or less structured working environment, machine learning can result in unpredictable behaviour on the part of the robot. Machine learning can also cause imperfections 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. Also, software components can contain bugs resulting in high-risk situations, e.g. activation of an unintended movement by the robot. The cobot's capabilities may be distributed in the cloud, for example, with the result that if one robot learns something, all robots can do it (if they find themselves in the same situation).

The cobot capabilities discussed below relate to semantic AI and were included in the interviews (a) to find out about the development of cobot systems in internal logistics and (b) to examine what safety effects these capabilities could entail.
The definitions set out below (apart from task complexity and adaptability) are taken directly from the MAR (2017)[20,21] and give a better understanding of various cobot capabilities. A cobot's capabilities are characteristic for the cobot but not developed to the same level as those of a human, and not entirely comparable. A cobot with a camera, for instance, can perceive at night, which we humans cannot, and it can process more data in a shorter time than a human can. Humans, on the other hand, are able to feel emotions, and this equips them better by nature to anticipate emotions. The capabilities discussed below give an impression of the extent to which a cobot has AI.

Perception:
Perception is the robot's ability to observe its environment. At the simplest level this involves specifying the likelihood of precise detection of objects, spaces, locations or items of interest in the environment of the system. It includes the ability to detect the movement of a robot arm, to interpret information and to make informed, accurate representations of its environment based on sensory data.

Recognition:
Many robot applications require the robot to recognize objects in its environment. This ability can range from recognizing a single object or many different objects to identifying objects that are consistent with a generic pattern, thus also enabling it to distinguish between people.

[20] Robotics 2020: Multi-Annual Roadmap For Robotics in Europe, Horizon 2020 Call ICT-2017 (ICT-25, ICT-27 & ICT-28), 2017
[21] Thrun, S. (2003). Learning occupancy grid maps with forward sensor models. *Autonomous robots, 15(2), 111-127.*

Prediction:

Prediction is a robot system's ability to gauge the impact of its own actions and other actions in the environment (in future). A cobot can quantify safety performance, for instance, and detect collisions in good time and anticipate them. Predictions will be based on different types of collaboration and may therefore require different levels of robot intelligence. Prediction depends on:

human detection and monitoring techniques, and algorithms or techniques for predicting movements, changes in circumstances and their effects and the actions required. The robot system is thus able to adapt its behaviour in order to subsequently carry out a task.

Cognition

Cognition (interpretation of 'sensory perception') is a process that gives a cobot the ability to understand how something could happen based on only partial information, either at the present moment or at a particular time in the future. The cobot is then able to adjust its behaviour. In order to predict the future the cobot needs to have a memory, so learning is vital for all cognitive systems. Cognition determines the extent to which the cobot can predict and to which the system is able to pro-actively and reliably operate, adapt and improve. It also includes the ability to model situation-action-reaction so as to predict behaviour. The cobot's learning and cognitive function are particularly important to enable it to react to changes in environmental factors that affect human-robot interaction.[22]

Human-robot interaction and interactive safety

Interaction is the ability of a system to interact physically, cognitively and socially with users or other systems, including robots. Ability to interact can range from a communication protocol to a sophisticated social conversation. This skill is vital, and depends on medium and context. Interaction takes place at various levels, i.e. physical, cognitive and social.

The requirement that all applications have in common is reliable, safe interaction between humans and robots in a shared workspace. Robots of this kind need to be designed carefully for long-term human compatibility. Robots need to reason, learn and act in close contact with humans, and they must make humans feel safe. Although the technology focuses on particular safety mechanisms, the entire system in its entire setting remains the decisive factor in the safety of performing a particular task. Safety can then be incorporated at various levels.

Decision-making autonomy

Decision-making autonomy is a cobot's ability to act autonomously. Almost all systems have a degree of autonomy, ranging from a simple movement that can be stopped as a result of sensory perception to the possibility of being self-efficient (using matrices) in a complex environment. With complexity and risks increasing in the working environment, the degree of autonomy and automation remains limited for the time being.

Transparency and feedback

In addition to intelligence, learning and reliability, Beer et al. (2012) mention transparency and feedback regarding the robot's status and intentions as important factors that affect

[22] Bekey, G.A. (2005). Autonomous robots: from biological inspiration to implementation and control. MIT Press.

human-robot interaction. In addition to the robot capabilities mentioned above, a cobot needs to be able to make a mental representation of its intentions for the user. Stubbs et al.[23] believe that this creates transparency for the user. They also looked at these human factors in relation to observation, planning and action, which are discussed in §3.2.5.

3.2 Research question 2:

This section provides information in response to Research question 2:

What are the expected or already manifest effects of these systems on actual – workplace and process – safety risks such as those that occur in industrial environments, and what control measures are there?

3.2.1 Risks relating to human-cobot-environment interaction

As regards human-cobot-environment interaction, three risk groups can be defined:

- risks to the cobot (which can often be traced to design and software programming);
- risks to humans; and
- risks to the working environment.

These are discussed in the following sections.

Cobot risks

In physical interaction with the operator in a more or less structured working environment, machine learning (sub-semantic AI) can result in unpredictable behaviour on the part of the robot. 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. Also, software components can contain bugs resulting in high-risk situations, e.g. activation of an unintended movement by the robot.

Security risks

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. Indeed, these types of risk will only increase as time goes by because of increasing AI in the software. Software risks therefore need to be reduced to an acceptable level by using tools to prevent potentially dangerous errors in software control. For more information see the 2016 TNO report, which has already looked at the cyber security risks of robots in some depth.

Environmental risks

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

[23] Stubbs, K., Hinds, P., & Wettergreen, D. (2007). Autonomy and common ground in human-robot interaction: A field study. IEEE Intelligent Systems: Special Issue on Interacting with Autonomy, 22(2), 42-50. DOI: 10.1109/MIS.2007.21

action, use of the robot in unstructured environments such as building sites or newly configured production lines).

3.2.2 Existing guidelines for risk identification and analysis for the safe design of cobots[24]

Various guidelines have been developed to control risks in the safe design of cobots, and they make a substantial contribution to the inherently safe design of cobots. ISO TS 15066, for instance, is a technical specification for the design of safe collaborative robots. Standards previously issued that were relevant in this area have become an integral part of this new standard (including ISO 10218-1:2011 and ISO 10218-2:2011 on industrial robots and ISO 12100 on machine safety) and should not be seen in isolation from the new standard. Indeed, ISO 15066 refers to those standards.

In order to identify the risks relating to the use of cobots in processes with associated tasks, the ISO TS 15066 standard also refers to carrying out a detailed risk identification and evaluation (RI&E) of the human-robot operation based on the principles in ISO 10218-2:2011. The classification for the risk identification and risk-reducing measures has to be ascertained from ISO 10218-2:2011, Annex A and ISO 12100.

Cobot producers, developers and systems integrators need to carry out a separate survey of specific process hazards based on joint human-robot activities and the respective tasks involved (e.g. welding and assembly) and the potential consequences for operator safety.

3.2.3 Technical design constraints for collaborative robots

A collaborative robot application needs to be designed in line with the special requirements for the control of collaborative robots (EN ISO 10218-1), taking predetermined tasks into account. The systems integrator also needs to carry out a risk assessment of the entire application, taking the following aspects into account:

- Cobot characteristics (speed, force, torque etc.).
- Tooling and workpiece risks (sharp edges, protuberances, moving parts, mass etc.).
- The design of the application.
- The location of the operator in relation to the robot (e.g. no activities beneath the robot arm).
- The location of the operator in relation to moving parts, brackets, clamps and any fixed objects in the environment (other machinery, walls, anchors etc.).
- Workpiece handling and related hazards (clamp design and position).
- The design and location of any manual control equipment.
- Risks due to the specific application (high temperatures, welding sparks etc.).
- Limitations on the operator due to use of personal protection equipment (PPE).
- Environmental conditions (radiation etc.).

Shielding and safety equipment need to ensure that users/humans cannot enter the non-collaborative area. If this does happen it must be detected, leading to a safety stop. Shielding must comply with EN 13857.

[24] Robotics 2020: Multi-Annual Roadmap For Robotics in Europe, Horizon 2020 Call ICT-2017 (ICT-25, ICT-27 & ICT-28), 2017

Sensing
In order to remove physical safety barriers and facilitate cobot-human interaction, devices such as light curtains and light grilles (IEC 61496-2), laser scanners (IEC 61496-3) and safety cameras (IEC 61496-4) must be used.
Future advanced systems will seek to use innovative solutions such as electro-sensitive protective equipment to detect humans or vehicles. If safety equipment is used to detect humans it must comply with the requirements of ISO 13856 for pressure-sensitive protective equipment (PSPE) or of IEC 61496 for non-contact detection equipment (ESPE).

Zoning
A recent update to the safety standard for industrial robots (ISO 10218-1 and ISO 10218-2) introduced a collaboration mode. ISO 13854, ISO 13855 and ISO 13857 are important reference documents for collaboration with cobots in a defined workspace. Examples of applications required in the working environment are as follows:

- The collaborative area must be designed so as to enable the operator to perform all his tasks with ease, with no risk of catching, cuts, puncture wounds etc. The position of equipment and/or machinery must also be such that no new hazards can be created.
- Safe spindle monitoring/limitation must be applied if necessary to limit the degrees of freedom.
- EN 349 for minimum distances between humans and robots, to prevent body parts becoming caught. Extreme limits (for the cobot, tooling and workpiece) and building constructions, machinery etc. must be applied if there is any possibility of hazards. If these distances cannot be enforced, additional safety methods are required.
- The area intended for collaborative use must be clearly defined and marked. It should be safeguarded by a combination of robot properties and safety equipment. The safety equipment should protect everyone involved in collaborative use.
- Additional zone and entry security systems may be needed if the risk assessment indicates that other people could gain access to the collaborative area and could be exposed to the hazards of the robot application.

Power limitation and prevention of physical injury in the event of contact
Biomechanical criteria for power limitation for collaborative robots are set out in ISO 10218-1, Section 5.10.5. Without shielding and/or safety equipment the design must comply with essential health and safety requirements for intrinsic safety:

- Maximum power and energy must be limited to a level at which no injuries could reasonably occur (see ISO 12100).
- The cobot itself, the tooling, the workpiece and any other parts of the application must not under any circumstances present a risk of e.g. catching, cuts, puncture wounds, hot surfaces, contact with electrical components etc.
- Multiple contacts must not result in injuries and/or damage to health (e.g. airways must be protected against harmful substances).

EN 10218-1 and EN 10218-2 set out various ways of controlling a collaborative robot:

Speed and position monitoring
The cobot should remain at a predetermined speed and distance from the operator. The functions are monitored by a safe system to detect the positions of the operator and the robot and the speed. Monitoring errors must lead to a safe stop.

The relative speeds of the operator and the cobot must be taken into account when setting the minimum safe distances in line with EN ISO 13855.

Safety-rated Monitored Stop
The cobot should stop and remain at a standstill as long as a human is in the collaborative area. The robot may restart automatically once the person has left the working area. The cobot should stop in line with certain programmed stop categories in line with EN 60204-1 (0, 1 or 2). Once stopped, the standstill must be monitored by a safety control system. Standstill detection errors should lead to a Category 0 stop (power off) in line with ISO 10218-1.

Manual control
The cobot should be moved at a limited speed (<250 mm/s) by an operator using a manual control. The manual control should be fitted with an emergency stop and have a hold-to-run function, and be positioned near the 'gripper'.
The reduced speed must be monitored by the safety control system and the maximum speed set in the risk assessment of the application. Speed monitoring errors should lead to a safety stop.

Human-centred design of interactive systems
Cobots are interactive systems that must be developed in line with human-centred design standards. ISO 9241-210 sets out the methods and criteria for taking proper account of user-friendliness (human-centred design), the use setting, user experience and user values during design, testing and implementation.

3.2.4 Overview of guidelines, directives and standards for the design and development of safe cobots

In addition to the technical and collective risk control measures mentioned above, Table 4 below gives a list of relevant standards as identified by Michalos et al. (2015).[25]

Table 4

EU Directives	Indicative general standards
2006/42/EC Machinery Directive (MD)	EN ISO 12100 Safety of machinery - General principles for design – Risk assessment and risk reduction
2009/104/EC Use of Work Equipment Directive	2004/108/EC Electromagnetic Compatibility Directive (EMC)
89/654/EC Workplace Directive	EN ISO13849-1/2 Safety of machinery - Safety-related parts of control systems Part 1: General principles for design Part 2: Validation
2001/95/EC Product Safety Directive	EN 60204-1 Safety of machinery - Electrical equipment of machines - Part 1: General requirements
2006/95/EC Low Voltage Directive (LVD)	

[25] Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., & Chryssolouris, G. (2015). Design considerations for safe human-robot collaborative workplaces. *Procedia CIrP, 37, 248-253.*

EU Directives	Indicative general standards
Robot standards	**Indicative general standards**
EN ISO 10218-1 Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots	EN ISO 12100 Safety of machinery - General principles for design – Risk assessment and risk reduction
EN ISO 10218-2 Robots and robotic devices - Safety requirements for industrial robots - Part 2:Robot systems and integration ISO/PDTS 15066 Robots and robotic Devices – Collaborative Robots	IEC 62061 Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems ISO 9241-210 (2010) Ergonomics of human-system interaction – Part 210: Human-centred design for interaction systems

3.2.5 What work risk factors are involved in human-cobot interaction?

In addition to the technical design constraints for cobots set out above, various work factors are involved in the well-being of employees and their safety behaviour in certain work situations. The factors found in the literature are summarized in this section.

<u>Physical capacity, cognitive capacity and job satisfaction</u>

Interactive safety is brought about by effective interaction between humans and robots, robust safe design and standardization. Pivotal human factors include the following: *physical workload, cognitive workload and job satisfaction.*[26] Parasuraman, Sheridan and Wickens (2008, pp. 145-146)[27] define mental workload as '*the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator*'. 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.[29] Tsang and Vidulich (2006) consider that there is also a link between mental workload and situation awareness. Situation awareness is discussed in the next section.

<u>Situation awareness</u>

Endsley (1995, p. 36)[30] describes situation awareness 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'.* 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 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.

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[26] RAAK PRO application (2014): HARRIE: Human Aware Robust Robotics Interacting Effectively

[27] Parasuraman, R., Sheridan, T.B., & Wickens, C.D. (2008). Situation awareness, mental workload, and trust in automation: Viable, empirically supported cognitive engineering constructs. Journal of Cognitive Engineering and Decision Making, 2(2), 140-160. DOI: 10.1518/155534308X284417

[28] Endsley, M.R., & Kiris, E.O. (1995). The out-of-the-loop performance problem and level of control in automation. Human Factors, 37(2), 381-394. DOI: 10.1518/001872095779064555

[29] Endsley, M.R., & Kaber, D.B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. Ergonomics, 42(3), 462-492. DOI: 10.1080/001401399185595

[30] Endsley, M.R. (2006). Situation awareness. In G. Savendy (Ed.), Handbook of human factors and ergonomics (3rd ed.), pp. 528-542. New York, NY: Wiley.

Trust, acceptance and satisfaction

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.[31]

Banh et al. (2015)[32] showed in their study that employees' opinions of robot capabilities (trust, impression of intelligence etc.) when assessing their jobs changed based on the robot's behaviour. Several studies have shown the importance of trust in and acceptance of robots.[33,34] Trust in robots has also been found to be an important factor in the decisions that people make in high-risk situations.[35]

A recently published article offers a framework for managing trust in automation.[36] Frameworks for trust have also been developed previously.[37,38,39] 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.[40] 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).

Team work can also enhance the safety of robot systems. Once robots gain substantial autonomous properties they should be regarded more as team players.[41,42] Lohani et al.

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[31] Waytz, A., Heafner, J., & Epley, N. (2014). The mind in the machine: Anthropomorphism increases trust in an autonomous vehicle. Journal of Experimental Social Psychology, 52, 113-117.

[32] Banh, A., Rea, D.J., Young, J.E., & Sharlin, E. (2015, October). Inspector Baxter: The Social Aspects of Integrating a Robot as a Quality Inspector in an Assembly Line. In Proceedings of the 3rd International Conference on Human-Agent Interaction (pp. 19-26). ACM.

[33] Desai, M., Kaniarasu, P., Medvedev, M., Steinfeld, A., & Yanco (2013). Impact of robot failures and feedback on real-time trust. In Proceedings of the ACM/IEEE Conference on Human-Robot Interaction, 251-258. Tokyo, Japan. DOI: 10.1109/HRI.2013.6483596

[34] Desai, M., Medvedev, M., Vazquez, M., McSheehy, S., Gadea-Omelchenko, S., Bruggeman, C., Steinfeld, A., & Yanco, H. (2012). Effects of changing reliability on trust of robot systems. In Proceedings of the ACM/IEEE Conference on Human-Robot Interaction, 73-80. DOI: 10.1145/2157689.2157702.

[35] Park, E., Jenkins, Q., & Jiang, X. (2008). Measuring trust of human operators in new generation rescue robots. In Proceedings of the JFPS International Symposium on Fluid power (Vol. 2008, No. 7-2, pp. 489-492). The Japan Fluid Power System Society.

[36] Metcalfe et al. (2017). Building a framework to manage trust in automation. Proceedings Volume 10194, Micro- and Nanotechnology Sensors, Systems, and Applications IX

[37] Desai, M., Stubbs, K., Steinfeld, A., & Yanco, H. (2009). Creating trustworthy robots: Lessons and inspirations from automated systems. In Proceedings of the Society for the Study of Artificial Intelligence and the Simulation of Behaviour (AISB) Convention, New Frontiers in Human-Robot Interaction.

[38] Hancock, P.A., Billings, D.R., & Schaefer, K.E. (2011). Can you trust your robot? Ergonomics in Design, 19(3), 24-29. DOI: 10.1177/1064804611415045.

[39] Hancock, P.A., Billings, D.R., Schaefer, K.E., Chen, J.Y., De Visser, E.J., & Parasuraman, R. (2011). A meta-analysis of factors affecting trust in human-robot interaction. *Human Factors, 53(5), 517-527.*

[40] Dewar, R D., & Dutton, J.E. (1996). The Adoption of Radical and Incremental Innovations: An Empirical Analysis. Management Science, 32(11), 1422-1433.

[41] Goodrich, M.A., & Schultz, A.C. (2007). Human-robot interaction: A survey. Foundations and Trends in Human-Computer Interaction, 1(3), 203-275. DOI: 10.1561/1100000005.

(2016)[43] consider that a human-robot team comprises two or more participants, each with a specific role or function, who interact dynamically and pursue a shared goal. As regards human-robot interaction, important skills are *reporting, communication, collaboration, coordination* and *team management*. Systematic reviews have found that the non-technical factors in Hancock's study (2011) have an average to substantial effect on trust in robots. Design principles that encourage situation awareness in human-robot teams[44,45] could also be tested and applied.

Beer et al. (2012) point out that robot autonomy with decision support (with the user taking the final decision) can be desirable in situations where it is important to leave correct decision-making to a human. Sycara and Sukthankar[46] describe the roles that collaborating robots can perform, along with some other important properties of human-robot interaction, such as team knowledge, mutual predictability and joint adaptation.

Emotional/social emotional skills

Lohani et al. (2016) argue that social emotional skills can provide a bonding mechanism for teams, as they are thought to increase participants' trust. The robot's humanness or friendliness is thus an interesting aspect that can affect employees' attitudes and degree of adaptation. 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.

Breazeal (2003)[47] considers that robots need to adapt to the social skills that people expect of robots, and this should be examined in relation to their autonomy. Social interaction with autonomous robots is best examined based on their social characteristics, e.g. appearance, emotions and personality (see also Breazeal, 2003).[48] These are aspects that also could be taken into consideration in the industrial design of autonomous systems for internal logistics.

Human-robot interaction experience/training

Wurhofer et al. (2015)[49] interviewed ten employees to see how they evaluated the added value of robots, work organization, feelings, social environment and attitudes over time, thus producing important research into employee experiences of robot implementation. A better perception of robots could result in better collaboration between humans and robots.

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[42] Milgram, P., Rastogi, A., & Grodski, J. J. (1995). Telerobotic control using augmented reality. IEEE International Workshop on Robot and Human Communication, 21-29. Tokyo, Japan. DOI: 10.1109/ROMAN.1995.531930.

[43] Lahoni et al (2016). Social interaction moderates human-robot trust-reliance relationship and improves stress coping.

[44] Endsley, M.R., Bolte, B., & Jones, D.G. (2003). Designing for situation awareness: An approach to human-centered design. London: Taylor & Francis.

[45] Gorman, J.C., Cook, N.J., & Winner, J.L. (2006). Measuring team situation awareness in decentralized command and control environments. Ergonomics, 49(12-13), 1312-1325. DOI: 10.1080/00140130600612788

[46] Sycara, K., & Sukthankar, G. (2006). Literature Review of Teamwork Models. Pittsburgh, PA: Tech. Report CMU-RI-TR-06-50, Robotics Institute, Carnegie Mellon University.

[47] Breazeal, C. (2003). Emotion and sociable humanoid robots. International Journal of Human Computer Interaction, 59, 119-115. DOI: 10.1016/S1071-5819(03)00018-1

[48] Steinfeld, A., Fong, T., Kaber, D., Lewis, M., Scholtz, J., Schultz, A., & Goodrich, M. (2006). Common metrics for human-robot interaction. In Proceedings of Human-Robot Interaction Conference, 33-40. Salt Lake City, Utah. DOI: 10.1145/1121241.1121249

[49] Wurhofer, D., Meneweger, T., Fuchsberger, V., & Tscheligi, M. (2015). Deploying robots in a production environment: A study on temporal transitions of workers' experiences. In Human-Computer Interaction (pp. 203-220). Springer, Cham.

Providing good, extensive training at an early stage so as to give employees a sound understanding of robots is thought to be vital to collaboration. 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.

3.2.6 Coactive design as a basis for safe human-robot interaction

HRI researchers Johnson et al. (2014) argue that interactive design, which they refer to as 'coactive design', should make joint activities by humans and robots possible. They distinguish between 'hard dependencies', which are needed to carry out a task together, and 'soft dependencies', which provide opportunities for carrying out joint activities. The Coactive System Model (Fig. 2) shows how capabilities relate to observation, planning, decision-making and action during robot-human interaction. Humans plan their behaviour based on their beliefs, intentions, needs, knowledge and experience, whereas robots implement a plan that follows from a particular perception based on software or AI algorithms. A shared representation of observation, planning (prediction), decision-making and action (control) is therefore needed while collaboration is taking place. This enables the functions of the human and the robot to be coordinated properly in a collaborative setting (as in the case of cobots, and to some extent in cooperative systems). (Clark's participatory actions[50] and Fong's system model[51]). The foregoing is developed below in terms of observation, prediction and directability:

- *Observation:* Clustering relevant aspects of a person's status, knowledge of the team, the task and the environment that can be observed by others.
- *Predictability:* Actions need to be predictable, so that others can count on them when considering their own actions.
- *Directability:* The ability to control behaviour and, complementary to this, to be controlled by others.

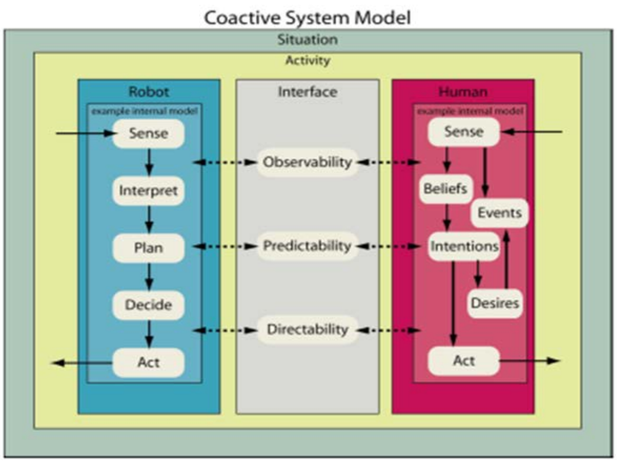

Figure 2: The coactive system model

[50] Clark, Herbert H. (1996). Using Language. New York, NY: Cambridge University Press. Retrieved from http://www.loc.gov/catdir/toc/cam023/95038401.html
[51] Fong, T.W. (2001). Collaborative control: A robot-centric model for vehicle teleoperation. Pittsburgh, PA: Robotics Institute, Carnegie Mellon University.

Task complexity:

Leva et al. (2017)[52] regard task complexity as the sum of physical and mental effort required to perform a given task. Complexity depends on the environment and cognitive capabilities, skills, training and experience. They base their definition on the performance model put forward by Rasch (1980).[53]

Adaptability (self-control versus collaboration)

The degree of self-control versus collaboration is the operationalization of degree of autonomy as opposed to dependence. In the view of Johnson et al. (2014)[54] a cobot's capability is the total set of inherent knowledge, skills, capabilities and resources that it needs to perform an activity independently. In the view of Bradshaw et al. (2004) the capabilities required are determined by the robot-environment interaction requirements, which can be associated with the autonomy dimension. If capabilities are lacking, dependence will increase in any given setting. A cobot operates independently if it has all the capabilities required to carry out an activity competently and safely.
Fig. 2 below shows the human-robot-environment interaction variables set out in §3.2 and §3.3. As noted above, the MAR was a particularly important document when it came to determining the robot variables. The interaction variables give an impression of the factors involved in safe human-robot interaction in the workplace.

The human variables are taken mainly from §3.5.2. The variables in the table provide the basis for the Human-Robot-Environment Interaction Model in Fig. 3, which shows that task complexity and robot capabilities and autonomy influence one another. The degree of autonomy and the robot capabilities required may differ from one task to another. Lastly, the environment in which the human-robot interaction takes place is an important factor in safe interaction between humans and robots, which is why working environment provides the setting for the model. The model developed on the basis of the theory in §3.2 and §3.3 provides an important framework for research into work risks and risk control measures in relation to collaboration with cobots. The interview questions specifically included questions on cobot capabilities, as these are indicative of the way in which risks (in combination with AI and in interaction with degree of autonomy) are controlled in the design.

[52] Leva, M.C., Comberti, L., Demichela, M., & Duane, R. (2017). Human Performance Modelling in Manufacturing: Mental Workload and Task Complexity.

[53] Rasch G., 1980. Probabilistic Model for Some Intelligence and Attainment Tests. University of Chicago Press, Chicago.

[54] Bradshaw, J.M., Feltovich, P.J., Jung, H., Kulkarni, S., Taysom, W., & Uszok, A. (2004). Dimensions of adjustable autonomy and mixed-initiative interaction. In M. Klusch & G. Weiss (Eds.), Agents and Computational Autonomy (Vol. 2969, pp. 17–39).
Berlin/Heidelberg: Springer.

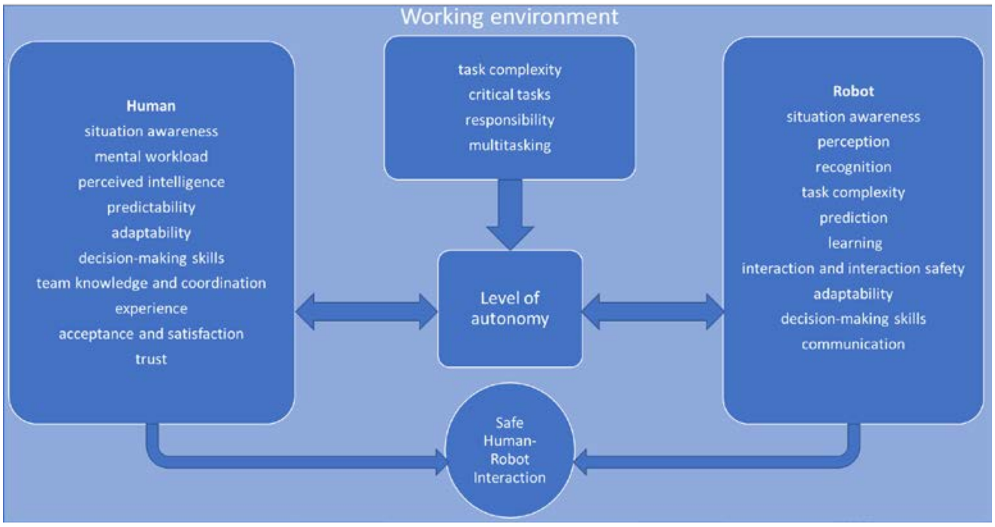

Figure 3: Factors for safe human-robot interaction

3.3 Research question 3

This section contains information relating to research question 3:

To what degree can existing technologies for analysing and managing risks be applied in working environments where autonomous robot systems are used, and do additional measures need to be taken?

3.3.1 Problem definition

The hazards described in the new Cobot standard ISO/TS 15066:2016 (Robots and robotic devices) can be used for the purposes of Risk Assessment and Evaluation.
However, TS15066 refers to ISO10218-2, Annex 1a, which itself is based on the ISO12100 standard for risk assessment and mitigation for designers in relation to Safety of Machinery. This means that TS15066 is based on the hazards described in the Machinery Directive. However, this directive does not completely cover physical human-robot interaction.
The standards mainly focus on safety risks of physical interaction, which is insufficient to guarantee safety at work, among other reasons because it does not cover cognitive interaction with robot systems, whereby ergonomic factors of the interface design play an important role in managing software and other risks.

Based on the aforementioned paragraphs found during the literature study, the researchers conclude that no specific list of hazards exists for working with cobots in which explicit attention is paid to the following forms of interaction:
1. Indirect interaction through a hardware/software interface
2. Cognitive interaction through gestures, speech or audio signals
3. Interacting environmental effects.

In addition, various standards (ISO10218-1, ISO13482) include design recommendations, but lack specific guidelines for risk analysis techniques. This also applies to the uncertainties involved with unpredictable robot behaviour, for example when applying fault corrections based on artificial intelligence. Such applications demand a high Safety Integrity Level (SIL; EN 62061) and/or Performance Level (PL; ISO 13849-1) (intended to safeguard ‘functional safety’) and are based on ‘statistical fault probability calculations’. Both are applied in various technical domains.

3.3.2 Risk analysis techniques

A risk analysis method for cobot systems would therefore need to meet the following requirements:

1. The method can be applied from the start of the development process (design) all the way through to the use of the product (operational management).
2. The method focuses on human activities as hazard source (deviations).
3. The method takes account of the capacities of the cobot (level of cobot autonomy and ‘intelligence’).
4. The method focuses on operational hazards resulting from the planned deployment of cobots (tasks) in interaction with humans and the cobot’s environment.

Currently, commonly used risk analysis techniques[55] for identifying robot risks include: Process Hazard Analysis (PHA), Hazard Operability Analysis (HAZOP), Fault Tree Analysis (FTA), Fail Mode, Effects and Criticality Analysis (FMECA) and Task Risk Analysis. PHA and HAZOP can be applied in the early stages of the development process, while FTA and FMECA focus on the advanced development stages and reliability aspects of robots. Robot-specific safety analysis tools have also been developed, such as HAZOP-UML[56]. HAZOP-UML is a risk analysis technique that combines HAZOP and the system visualization language UML (Unified Modelling Language). It was developed by LAAS-CNRS (Guiochet *et al.*, 2010[57], 2013[58]; Martin-Guillerez *et al.*, 2010[59]), and is used in industrial contexts. A selection of key words is applied to the UML diagram to conduct the deviation analysis. The output of a HAZOP-UML is a list of hazardous situations, an analysis of potential consequences, a series of recommendations and a list of hypotheses.

The main advantages of HAZOP-UML are its simplicity, the fact that it can be applied during early development stages, and its systematic, model-based (models can be shared during the development process) and user-friendly nature.

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[55] Guiochet, J. (2016), *Hazard analysis of human–robot interactions with HAZOP–UML*, *Safety science*, 84, 225-237.

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TRA

The Task Risk Analysis (TRA) is mainly used to scrutinize a limited number of high-risk tasks. The analysis is often used to enhance the tender process. However, a traditional TRA will be insufficient for analysing cobot risks. As described in this report, risks involving cobots are more dynamic because of a) interactions between robots and humans/environments, and B) the diversity (capacity) of robot systems. These variables will jointly determine which potential risks (unsafe activities/situations) will apply.

Bow-Tie and Storybuilder

Analysis methods like Bow-Tie or Storybuilder do not classify risks according to severity (of the effect). These methods do not allow the user to quantify effects (as RI&E and HAZOP do). The Storybuilder method can, however, provide information about the course of an incident, the factors that caused the situation, and it can use big data (cause effect-relationships in Storybuilder) to predict the failure probabilities of events. However, Storybuilder does not currently include incidents with robots (that is to say it does not specify whether an incident with a machine concerns a traditional machine, a robot, or a cobot; it only refers to incidents with machines in general). Bow-Tie is used to analyse risk scenarios and identify threats, effects and risk management measures for a main event. Storybuilder and Bow-Tie both offer options to illustrate scenarios to users, enabling the target group to learn how accidents with cobots could occur in practice.

The HAZOP method

Considering the above information, the HAZOP method appears to be the most suitable risk identification method for analysing robot safety. Annex C contains a table that illustrates part of the HAZOP method. HAZOP has the following benefits:

1. HAZOP can be applied in both the design and operational phases. The HAZOP method can also be applied to non-physical or technical risks, such as procedures for managing complex processes (e.g. batch processes).
2. The HAZOP method combines two types of analyses: predictive research and operations research. Events and situations involving a fault or deviation are used for the predictive analysis. The assessment of ‘system reactions’ (reactions involving human-robot-environment interaction) to deviations is particularly applicable to human-cobot interaction. The cause analysis of these system reactions is determined during the operations research. The method focuses on identifying influences that prevent the cobot from strictly performing its functions as it was programmed to do.

The HAZOP method can be expanded with a system modelling language such as UML (Unified Modelling Language). This method was jointly developed with LAAS and successfully applied in various French and European projects (PHRIENDS, 2006-2009; SAPHARI, 2011-2015; MIRAS, 2009-2013) in cooperation with robot manufacturers (KUKA Robotics, AIRBUS Group and Robosoft).

4 Interview and workshop results

This chapter summarizes the results of the interviews and the workshop. An overview of the opinions and suggestions made by the interviewees and workshop participants is provided below. The interviews focused on AGVs as a cobot system use case. We explain how AGVs are a subclass of cobots in section 3.2. We have limited this section to AGVs because:
a) AGVs are used in practice relatively often.
b) AGVs are mobile and so interact more with humans.

The interviews and the workshop focussed on answering research question 2:

‘What are the expected or observed effects of these systems on existing occupational and process safety risks as these occur in industrial environments, and which risk management measures are in place?’

The key interview findings concerning risks and management measures are described below. These themes have been divided into four subthemes:
(1) preventing unsafe robots by using an inherently safe design, (2) human error in human-robot interaction, (3) robot failure in human-robot interaction, (4) mistrust of AGVs at work.

Preventive and reactive risk management measures are described in sections 4.2.5 and 4.2.6 for two themes that were extensively discussed during the workshop: (1) mistrust of AGVs at work and (2) collisions between traditional machines or AGVs and humans. Finally, in the last section, we take a look ahead by asking the participants to predict what will change in the area of risks and risk management as AGV systems become smarter and more autonomous in the future.

We will start with a number of examples from cobot practice that were provided during the interviews in response to the research question:

‘What are the latest autonomous or semi-autonomous robot systems?’

4.1 Research question 1: What are the latest autonomous or semi-autonomous robot systems?

A number of AGVs were the focus of discussions in relation to risks and risk management during the interviews. These are listed below in Table 5.

Table 5: AGV types

AGV	Description
Forklift AGV	This AGV accompanies an employee who is collecting orders within a predetermined time limit using a voice-picking system. The employee also stacks orders in roll containers in a prescribed manner and seals and labels these containers before they are brought to the loading dock. The employee operates the electric order picker and changes batteries at the charging point. By pressing a button on a wireless 'transceiver' glove (Crown QuickPick), the vehicle can be remotely directed to the next pick-up location without having to return to the operator's compartment first, so that the operator can remain in the optimum position for order picking. The roll containers no longer need to be transported back and forth to the dock, which means 15% less manoeuvres.
Kiva robot (Amazon)	This mobile AGV collects pallets with products from the warehouse and brings them to an employee who selects items and packages them for delivery. https://www.youtube.com/watch?v=JXkMevbjga4
Omnimove	Omnimove is a large automated mobile platform with omni-directional wheels that allow it to turn on its axle and drive sideways. It is used to move aerospace parts (airplane hulls and wings) and transport train carriages in relatively confined spaces. The Omnimove can transport weights of up to 50 tonnes. https://www.youtube.com/watch?v=kN9a7W_hnSQ
Automated mobile platforms	These are automated AGVs that travel a pre-programmed route along a physical track or using GPS or sensors. Some of these platforms can update their route program using SLAM navigation.
Mobile robot with robot arm	This is a cobot mounted on an AGV. https://www.youtube.com/watch?v=ymAgKyMF82s

4.2 Research question 2: What are the expected or observed effects of these systems on existing occupational and process safety risks as these occur in industrial environments, and which risk management measures are in place?

The answers to this research question will be discussed in light of the following themes:

4.2.1 Preventing unsafe robots by using an inherently safe design.
4.2.2 Human error in human-robot interaction.
4.2.3 Robot failure in human-robot interaction.
4.2.4 Mistrust of AGVs in the workplace.
4.2.5 Collisions between traditional machines and humans.
4.2.6 Collisions between AGVs and humans.

4.2.1 Preventing unsafe robots by using an inherently safe design

The best way to manage the risks is to design safe AGVs. Various standards exist that oblige producers and system integrators to take account of certain important safety requirements in the design. Most of these requirements were described in earlier sections (see 3.2.2 to 3.2.4) and a number will be described in section 4.2.1.4 'Design safety standards'. The technical design measures are described in sections 4.2.1.1 and 4.2.1.2, and the RI&E methodology in 4.2.1.3. The RI&E is the foundation for defining the standards that must be applied to a design. A number of important standards will then be explained in the last section.

Hardware: Technical design measures

The main design measures to reduce the impact of risks are: maximum weights, power reduction measures, maximum speeds in specified zones,
maximum AGV capacities and loads, and bumpers made of soft materials. There are also various measures that can be taken to ensure safer routing. In the event of an obstacle (such as an operator walking in front of the machine), an AGV's safety sensors can detect the object so that the AGV can adjust its speed accordingly. If the operator gets too close, the AGV will stop, also with the use of a sensor.

If an AGV drives into a pothole or over a bump in an uneven floor, it may wobble and cause its field of vision to change. With the current state of the art, an AGV's observation capacity is usually limited to a visible field or plane in a single direction. This field or plane changes depending on the focus of the camera. Environmental factors such as uneven floors should therefore be controlled as much as possible and must be taken into account in the general safety policy of the organization that uses the AGV. One source measure that can remove this risk is including 3D or 4D visualization cameras in the design of the AGV.

AGVs create a map of their environment using mapping technology. This involves scanning the floor and converting the data obtained into a map. Approved and prohibited zones are pre-programmed in the system.
One risk of these systems is that something in the environment could change. The AGV will not recognize this change unless a new map is created. One way to mitigate this is a Safe Move function. This function gives the AGV a certain degree of freedom to move within a predetermined area. The Safe Move function continually scans the AGV's work area and automatically shuts down the AGV if someone enters this area.

Most AGVs can only communicate visually by providing status information on LED displays. However, some cobots can also communicate by making specific gestures. These can be interpreted by employees as 'signs' or 'signals' and so make it easier for them to predict the behaviour of the cobot. Cobots also have control panels with SMART pad interfaces (screens that display the current status of the cobot). The same technology could also be applied to AGVs. There is as yet no standardized communication protocol for verbal interaction between employees and AGVs. Such protocols are problematic, because they require employees to use cue words to communicate in emergency situations and it is not easy to determine the most suitable cues ('whoa' or 'stop').

Agreements must be reached on how hazards will be communicated by both users and the autonomous AGVs of the future.
In some cases, the AGV can be reprogrammed so that the voice-picking system recognizes a particular user and adapts to them. This makes it easier for the user to understand, interpret and control the AGV.

An AGV must always have an emergency stop system. The requisite sensors should be installed on all sides of the AGV to enable it to respond to various situations. An AGV can also be stopped by pressing a special button. The automated activities are then overruled and the AGV will continue to operate in manual mode (i.e. no longer autonomously).

Heavy AGVs have emergency brakes as part of their intrinsic design. However, emergency brakes can also form a risk in case of faults; if the hydraulic pressure fails, then the emergency break will not function, or the brake will fail to disengage after an accident, posing a hazard if an employee has become trapped. To prevent this risk, AGVs must be fitted with reliable pressure cylinders that ensure the brakes can be activated and deactivated in all situations. Brakes need to be adequately illuminated where possible and users need to be provided with clear information about the fault so that they can respond appropriately. Clear requirements to this end could be included in the Machinery Directive.

Many control systems cannot be certified, which is why the physical safety of the robots needs to be safeguarded by another means. To this end, a 'Safety PLC' (Programmable Logic Controller) is assessed against various standards. These standards ensure that the software is not too easy to manipulate, for example. The Safety PLC verifies a number of safety conditions and a system is classified unsafe if any single condition fails to be met. To this end, the Safety PLC amounts to a 'blueprint' of the AGV's pre-programmed baseline safety data. The instrument enables robust monitoring of safety-related functions (zones, height, speed and acceleration) to prevent physical contact with humans.

Some mobile platforms have 7-axle robot arms, all of which contain a pressure sensor. If the maximum allowable pressure is exceeded, the AGV automatically stops. The robot arm measures the torque (pressure or no pressure?) and will continue the program if it detects there is no pressure. The advantage is that the AGV does not have to be restarted, but there is a risk that the arm has to actually make contact to detect a hazardous situation. The movement safety of the mobile platforms is safeguarded by continuously monitoring the speed of the robot. The robot automatically stops if the maximum speed is exceeded and the operator receives a warning. If the Safety PLC can no longer guarantee this safety level, there will be a risk of damage.

Some large logistics AGVs can detect objects that are far away using a laser scanner (Lidar technology). The disadvantage of using laser technology in AGVs is that it only detects objects between specific height ranges. This means that only part of some objects (humans) will be detected. Lasers are also inhibited by object shadows; if the AGV moves behind an object, it will not be able to detect other objects in the vicinity. This necessitates a smart sensor that can detect if a human is present in a specific zone. and would have to be a camera that can distinguish between humans and machines. Much can be achieved by combining a 3D camera (such as a Kinect) with thermal imaging. One problem with this technology is that it does not offer the desired reliability for this application.

If an object is detected, the AGV will modify its speed based on a predetermined profile. If an object is very close, the AGV will stop automatically; if this system fails, the AGV has a backup safety mechanism in the form of a bumper (direct stop), which requires a laser curtain and bumper sensor. The final barrier is a safety relay which activates a kind of handbrake. The risk of this is that an unsecure load could fall off the AGV when it brakes. An alternative to a camera – and additional safety barrier – is to place mats on the floor (if an operator is detected in the zone then the AGV halves its speed) or to use lasers.

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. The AGV can only carry a relatively limited array of sensors (due to the limited capacity of the processor and the battery), which reduces the reliability of the AGV in these situations. Robot developers and system integrators can learn much about human-robot interaction in industrial AGV and cobot applications from the social robot domains, including healthcare.

To improve human control of AGVs during human-robot interaction, light AGVs could be fitted with similar manual functions to those used on cobots. Operators can command cobots to switch from task A to task B and then task C by pushing the cobot's arm in the appropriate direction. If there is a fault, the operator will see a fault warning which can also call up the manufacturer's technician to provide assistance. Some cobots can produce physical signals. Cobots can be given explicit instructions and be programmed by an authorized user using a 'teach pendant', further improving their controllability by humans. In this manual mode, they can be forced to carry out manoeuvres.

AGVs still have limited predictability. Teach pendants have a simulation mode that can be used to predict what a cobot will do if it is programmed in a certain way. A similar function could also be devised for AGVs in the maintenance mode. Both cobots and AGVs normally display continuous pre-programmed behaviour to which humans will mostly adapt. In contrast to AGVs, however, cobots are often in control of the production line and determine its rhythm (controllability). Cobots are not yet capable of autonomously adapting their programs to their environment, for example if they are working too quickly for a human to keep up with them. This will also need to be taken into account in interactions with AGVs (for example when handing over tasks).

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. The risks of interaction between AGVs and users in such situations will need to be identified. A protocol could be drafted that prescribes which users (e.g. operational managers, fleet managers and emergency responders) may overrule an AGV in certain situations.

Physical design risks

Physical risks can be divided into two main categories:

1. Risks that arise from robot designs.
2. Risks that arise from the functional use of the AGV (tooling).

The system integrator is responsible for identifying the risk scenarios. The risks depend on the application the AGV is used for (and in cobots also on the materials used in the end effector). The starting point for a comprehensive risk analysis is the use of common sense. An RI&E is then conducted to determine a safe system design. First the critical components are pinpointed and then the limit values of the design components (power, speed etc.) can be calculated based on standards.

The standards for robot grippers used in different applications are based on (1) the task and function, (2) the gripping technology used, (3) the products the robot manipulates, and (4) how the software can be programmed.
The applications that a cobot or AGV is used for must also meet certain standards. In some cases, a threshold will apply. For example, a robot may need to take curved surfaces into account when manoeuvring at eye level. This means the end user shares responsibility for determining whether an application is safe.

The following design risks will need to be managed:
- *High-speed collisions*; managed by speed limiters and position controllers (zoning plan).
- *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).
- *Tooling*; e.g. impact and speed are required to be lower at eye level than at stomach level.
- *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.

Risk analysis and incident management
The current RI&E methodology based on ISO-13849-I and ISO 12100 could be expanded by collecting statistical data. This improves the quality of the safety management system by allowing risks and measures to be analysed more accurately in advance.

An important collective measure is the registration of near misses caused by unexpected behaviour. By sharing information about the robot and its software throughout the supply chain, the lessons learned can contribute to improving both the software and the hardware. The current method of analysing risks using RI&E needs to be improved because it only provides qualitative data. If a quantitative data collection method could be standardized, this could contribute to improving the RI&E. This would already provide a benefit if you could specify the three key risks. Various universities and knowledge institutes are currently conducting tests (e.g. on maximum forces that can be applied on humans). These tests could be expanded to include controlled experimental research. Following an incident, it is difficult to analyse a scenario based on hindsight; this is easier to do in a controlled setting. For example, practical examples of hazardous situations could be tested in this way. A problem here is that robots can change, so there is a risk of conducting tests on outdated models.

In case of emergencies, AGVs must be able to make their way to a safe location where they cannot be a source of further escalation, for example to avoid batteries overheating and exploding. Incident data should be able to be retrieved from the building management system that is linked to the AGV and the fleet manager.

Manufacturers should be required to report ‘good practices and lessons learned’ to ensure the entire supply chain is kept informed. The safety lessons can then be incorporated in new AGV hardware and software. Appropriate information should also be provided about the changes. The user manual must be written in the customer’s own language and the known hazards should be described in this manual.

Safety standards for inherently safe AGV designs

The interviews cited a number of standards that are used in the design and production of cobots. This information is supplementary to the standards described in sections 3.2.2, 3.2.3 and 3.2.4. The designer of the AGV will need to meet the safety requirements set down in legislation pertaining to safety, health and environmentally safe use of AGVs. The standards described below are used to this end. The system integrator is responsible (together with the organization) for establishing which standards apply based on a risk analysis of the relevant application.

- EN ISO 12100-1/2 Basic concepts, general principles for design.
- EN ISO 13849-1:2008 Safety-related parts of control systems – Part 1: General principles for design.
- EN ISO 13850:2008 Emergency stop – Principles for design.
- EN 1525 Driverless trucks and their systems.
- EN 349+A1:2008 Minimum gaps to avoid crushing of parts of the human body.
- EN ISO 14121-1:2007 Risk assessment – Part 1: Principles.
- EN 60204-1 Electrical equipment of machines – Part 1: General requirements.
- IEC 60204-2 Electrical equipment of industrial machines – Part 2: Item designation and examples of drawings, diagrams, tables and instructions.

- Electromagnetic compatibility (EMC):
- EN 61000-6/4 Part 6-4: Generic standards – Emission standard for industrial environments.
- EN 55011 Industrial, scientific and medical (ISM) radio-frequency equipment.
- Electromagnetic disturbance characteristics – Limits and methods of measurement.
- EN 61000-6-2 Part 6-2: Generic standards – Immunity for industrial environments.
- EN 61000-4-2 Part 4-2: Testing and measuring techniques – Electrostatic discharge immunity test.
- EN 61000-4-3 Part 4: Testing and measurement – Section 3: Radiated, radio-frequency, electromagnetic field immunity test.

Commissioning and implementation

A fleet of AGVs can be controlled by linking them to an ERP system. The individual AGVs are the logistical links that connect the various production ‘islands’. The goal is to increase the productivity of the employees. Software management standards are in place to ensure safety is improved, which can be distinguished according to the degree of autonomy of the systems. For example, a train or other potentially hazardous machine will be subject to more stringent requirements in terms of its autonomy. The EN-ISO 13849 standard concerns the safety-related parts of control systems (SRP/CS) based on a Performance Level (PL). The PL describes the degree to which an SRP/CS can fulfil a given safety function (under foreseeable conditions). Five Performance Levels are recognized (A to E, whereby A is the lowest level and E the highest). Machines are always commissioned based on the traffic light model:

1. Does the product meet the procurement standards?

It is important to assess whether the manufacturer has programmed the product according to the specifications before it is taken into use. Cobots such as the Yumi are programmed with a safe mode to this end, which allows the robot’s behaviour to be simulated in 3D. This enables the user to decide whether any modifications will be required for practical use.

The user can also simulate the robot's behaviour step by step by using a joystick to 'jog' through the process. Special software is used to analyse, visualize and record the robot's moving parts in a VR environment.

2. Is the commissioning certificate visible and has a voltage check been conducted?
While the manufacturer must meet the CE standards, the system integrator and the user (customer) are also required to have safety assurance systems in place, including the integrator's safety instructions. The instructions are based on various product manuals. Some companies have in-house system integrators. The appointment of a system integrator is currently only subject to self-certification without external requirements. In case of incidents, the company must be able to demonstrate that its self-certification process is adequate. The end user must assess whether the system integrator has adequate and up-to-date knowledge and information on the relevant system. The system integrator must be able to demonstrate that they have complied with the ISO standards.

The efforts to make the system safe should be shared with the end user as part of an open company culture. A culture of litigation could result in this process stagnating. By sharing the lessons they have learned, the system integrator can help ensure that other end users are aware of the risks. A format could be developed for sharing such information. The manufacturer could provide system integration support to the integrator using this format.

3. Have the employees followed appropriate training?
Once you have assured and tested the quality of the hardware and software, the next step is to provide the employees with training. Employees should have basic knowledge of the AGV's capabilities in case of emergencies. This should lead to more awareness of the AGV and the risks related to its use, and will encourage employees to learn more about the AGV and so prepare them for working together with it. Manufacturers should only officially hand over an AGV system if they are confident the relevant employees are sufficiently competent to work with it. An AGV system can also register certain information by means of incident logs. This includes information on the employees who were involved in a fault, incident or near miss.

Some manufacturers require the customer to appoint a fleet operator. The fleet operator is responsible for the AGV system as a whole. The fleet operator is provided with special training by the manufacturer (system integrator). A number of core responsibilities are defined in relation to the ISO management system.
1. Responsible for the continuous operation of the fleet.
2. Resolves AGV issues in case of stagnation.
3. Trains employees to work with or in the vicinity of AGVs.
4. Defines collective measures (AGV zoning and demarcation in relation to other employees or third parties).
5. Familiarizes the employees with the general house rules and codes of conduct for working with or nearby AGVs.

4.2.2 Human error in human-robot interaction
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, which is explained in

more detail in sections 4.2.2.1 to 4.2.2.4. These sections also describe various risk management measures.

Use and maintenance of cobots/AGVs
Manufacturers can share the practical knowledge they have gained of potentially risky cobot/AGV manoeuvres with their customers. Some cobots make inefficient turns, for example, which could be improved in some cases. Experiences of risky situations caused by human action gained from practice could be shared with R&D departments so that they can update the RI&Es and improve the products. The next step for manufacturers and system integrators could be to update the RI&E based on the occupational safety and health strategy.

Programmers may accidentally build risks into an AGV's software (if too little account is taken of the risks in the working environment). An example is an AGV that has been programmed to travel 10 km to a work location. The software program determines the risks along the route. For example, it must integrate all potential obstacles such as locations where hydraulic oil leaks are likely. This risk can be avoided by a good design (with zoning plan) or by keeping to work agreements on orderliness and tidiness (good housekeeping). It may be desirable to limit the capacity of the AGV for this reason. A highly autonomous AGV whereby the operator has to define what it is *not* allowed to do is much more difficult to control than an AGV that can only follow an operator's commands.

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. A source measure that could solve this problem is to draw up additional use protocols (regulations) that specify that the system integrator must test all software updates and versions of all AGVs to determine if they have the same output. This is currently already a requirement for automobiles.

The employer is also responsible for implementing a management of change procedure that ensures the appropriate documentation is provided for every software (code) change. It is the system integrator's responsibility to update this information. The management of change procedure is used to identify and repair faults and communicate this information in the organization. This also helps ensure that the appropriate persons authorize the changes. If an AGV is given a new role, this must first be subject to a risk analysis.

Managing risks involving faults
To prevent the risk of accidents caused by faults, the AGV's software should retain the current status (fault code) of a fault until the operator has confirmed it. A short power disruption during an emergency braking manoeuvre may involve a risk that the AGV will roll back and crush an operator.

The course of an incident may depend on whether or not the emergency stop button is operational. For example, in case of a fire, all power to the AGV must be turned off (as long as it is inside a safe zone). Appropriate and easily interpretable warning signals (LED lights) should be used to avoid incorrect diagnoses by users.

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. A standard for software and hardware modules such as modular grabbers, sensor systems and navigation modules is currently under development. The modules also require built-in safety and security features at the system level to ensure safe application of the modular systems.

Mindware: reducing human error
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).

An emergency stop is of critical importance to be able to bring the entire AGV system to a halt or to give other AGVs right of way (as long as the stationary AGV does not form a risk to its surroundings). Another way to prevent this risk is to separate logistic flows, for example by means of separate logistic zones. A distinction can be made between manual work and automated processes, or between time zones (e.g. no manual procedures between 09:00 and 13:00, and interfaces between 17:00 and 22:00). These are collective risk management measures to prevent collisions.
Other measures that can be taken include driving slowly (0.3 m/s) in the vicinity of a work area, individual personal safety measures (such as lines on the floor that demarcate areas an employee may not enter) and wearing appropriate personal protective equipment. The provision of warning signs can help to increase situational awareness. Deliberate and accidental infringements of prohibited zones can be prevented by providing and enforcing clear work instructions.

Pre-programmed routes will be protected with passwords. Only authorized persons can program a cobot and the associated software platforms using a unique safety code. To ensure there is no electrical shock hazard, the cobot can be deactivated with a key (physical or digital) before maintenance work or to resolve a fault.

The service engineer must first deactivate the AGV using a lock-out tag-out procedure before working on it. This entails shutting down the AGV or setting it to manual operation and informing other employees and visitors in the area.

One way to increase situational awareness and knowledge of how to respond to risks is to provide employees with a training course of a number of days including do's and don'ts, an explanation of the work instructions, theoretical and practical training and a test (including a certificate).
In case of an incident, a compulsory certification system will demonstrate that the involved employee was trained and should have been aware of how the system works.
There are a number of minimum requirements for competences and skills: users should function at least at the secondary vocational training level. If you are able to use MS Outlook, you can also control an AGV system. Users must be able to interpret and resolve fault codes. Users must be able to operate 2D/3D navigation software (green = OK, orange = fault, red = issue) and have affinity with technology.
Only trained employees who are aware of the risks may transport large AGVs to a safe zone. It is also essential to be familiar with the AGV's programmed behaviour.

Aggression
Incorrect and inappropriate use of robots appears to take place predominantly during night shifts. Deliberate or accidental sabotage (such as placing objects on the AGV's route or failure to respond quickly to fault warnings) and even wilful damage (such as driving a forklift truck into an AGV) can occur. To prevent wilful damage by employees who are inadequately prepared for the AGV systems, both day-shift and night-shift employees should be informed about the implementation of the systems, and be trained in their use, as early as possible.

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. Another last-ditch way to prevent employees from damaging an AGV is to mount a camera on it to detect potential molesters. However, this suggests an underlying lack of trust within the organization that needs to be resolved. This is the reason why employees should be involved in a project involving robots from the very start (the commissioning phase). This can foster the support of and a sense of ownership among the employees.

Physical risks and the predictability of human-robot interaction displays
Intended users of AGVs are often only actively approached if maintenance is required or a fault occurs. Employees working nearby AGVs will not always be aware of what the AGV is doing.

Although lights and displays are used to provide information about faults, some systems have as many as 350 fault codes. Large numbers of fault codes combined with complex systems make it difficult for an operator to analyse the condition of the robot. Moreover, if the AGV fails to provide full status information, this can lead to an incorrect diagnosis. Some faults are not completely documented with clear follow-up procedures for the user, while many of them will require action by the user. Safe human-robot interaction must also be guaranteed by the HRI design and the corresponding ergonomic interfaces.

Examples of risk scenarios can be found in the automotive industry. More autonomous logistic processes result in more options built into the AGV's software, which in turn leads to

more risks for human-robot interaction. For example, for efficiency reasons, an AGV may be programmed to switch off if it overheats. When the temperature falls below the overheating threshold, the fault status will be cancelled and the AGV can continue its tasks.
An abrupt change in such a situation in combination with limited observability of the AGV's status and scheduled behaviour can result in accidents. A potential scenario is provided below in figure 4.

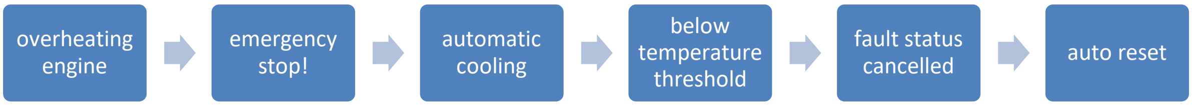

Figure 4: Emergency stop scenario

A similar scenario can be applied to electric motors. The electric motor is powered by a battery that is charged by a combustion engine and dynamo. If the battery is too low, the combustion engine and dynamo switch on to recharge it. This entails a change to the status of the AGV. Because the combustion engine is running, someone with insufficient knowledge of the system could assume that the AGV must be out of action. This poses a risk if the AGV is abruptly activated and moves once its battery has been charged to a minimum level. This is particularly a risk if the engineer and/or AGV is partially hidden from view so that neither can properly assess the situation. The interaction between the environment and the status of the AGV makes it all the more important to distinguish between various types of fault statuses which can each have different causes (e.g. observability or mobility).

If the operator has insufficient control of the AGV's status, programmed processes that have been insufficiently communicated with the users can form a risk. It is very important to have a clear description and understanding of how the AGV will behave in these situations.

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. It will be necessary to specify residual risks (risks that cannot be managed in the design but only in the work process) and determine what information needs to be communicated with the user. It is important to prevent an overabundance of information about residual risks.

AGVs that can be programmed to auto-reset and drive independently have a potential risk built into their software. A joint risk management vision needs to be developed in relation to system faults and the way the AGV communicates these to its environment (users and others).

The challenge for HRI is to develop an interface that covers all statuses (including risk statuses) and that communicates clearly, in a way that is not open to more than one interpretation. The following aspects will need to be considered carefully, among others:

- *Safety interface*. The creation of fault categories and a manageable number of aspects to be communicated.
- *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.

- *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).
- *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:
  - Is the freedom of the AGV limited (autonomous mode) or not?
  - What is the AGV able/allowed to do in this situation?

The programmer could include the mechanic (or the mechanic's van) and situational factors in the overall logistic AGV system, so that the mechanic and the environment become part of the process. This increases the visibility of the human-robot interaction, so that risks can be identified sooner. Different kinds of AGVs limit physical risks through different kinds of designs. More universal solutions could be designed to increase the situational awareness of the user in relation to managing occupational safety risks in interactions with the AGV.

4.2.3 Robot failure in human-robot interaction

Artificial Intelligence

The internal logistics sector has not yet reached the machine learning phase of Artificial Intelligence (AI). It is expected that this will take some years yet. An AGV's decision-making is based on authentic navigation (gyroscope using traditional x and y coordinates) and is programmed in its software. This means that an AGV can only move between two points if it is programmed to do so. However, new navigation mapping techniques have been developed that enable an AGV to detect objects and collision risks and respond by turning left or right. Examples are SLAM and Lidar.

Industrial AGVs are likewise currently still unable to learn by gathering and communicating real-time information. For now, their degree of autonomy, which is influenced by such learning capabilities, is limited by their programming. Cobots and AGVs must heed the commands of humans and are currently still unable to control processes. This means that an AGV cannot modify its own processes yet either, for example by skipping step X1, remembering this, and carrying out the step at a later time. If something goes wrong in the process, it is often the employee or operator who has to rectify the fault and manually reactivate the AGV.

Risks of autonomous systems with AI

If an AGV's power source is disrupted, it may brake hard and abruptly. The AGV adapts its behaviour based on its software. The more algorithms programmed into an AGV, the less predictable it will be. This means it is also difficult to predict if the selected solution to a given problem will be the right one. However, there is a new development in cobot design: *Teach by Demonstration.* This is a safe learning mode that is used with some cobots and enables the operator to direct the cobot from point A, via point B, to point C, whereby the cobot learns to replicate the commands itself. However, the system has not been developed to the extent that highly specific and accurate manoeuvres can be adapted by the cobot. For example, to close the end-effector (the tool on the end of the robot's arm), the operator has to program the manoeuvre in the software.

The automotive industry is currently using algorithms to develop recognition and demarcation of traffic signs (based on video and speed recognition). The information is passed on to a main database, where a central computer improves the algorithms.
The result is self-learning algorithms that learn from the knowledge that is collected. The algorithms can change the speed of the vehicle based on real-time information. AGVs are not yet able to assess risks in a similar manner. That is why limiting the freedom of AGVs is still an important risk management measure.

AI and the predictability of human-robot interaction
With the current palletization systems, the diversity and movements of cobots are still limited and so only a few degrees of movement need to be defined. Cobots are currently deployed for specific applications (defined by task and objective) such as palletization, packaging, gluing stone strip to prefab walls and navigation test systems. *But what will happen when robots have access to machine learning?*

The predictability of the cobot's behaviour will become much more important. A manoeuvre that seems unpredictable to a human could be completely logical to a cobot or AGV, with all the risks for occupational safety this entails. A limitation of software is that it is difficult to define and program what a human experiences to be unpredictable when working with or nearby AGVs or cobots. Another risk is that unpredictable AGV behaviour can make people feel insecure and subsequently anticipate unexpected situations based on this feeling of insecurity. As such, this unpredictability can lead to unpredictable behaviour in humans, which in turn leads to a risk of incidents.

For example, consider a cobot that moves a box from A to B and has six degrees of freedom to do this. The cobot has been designed with powerful shoulder joints (but not the other joints). Having strong shoulders, it may be most efficient for the cobot to move the box by sweeping it around with outstretched arms, but this poses a risk to humans in case of an impact (due to the strength behind the movement). So it is important to take account of the human factor when defining the algorithm; not just physical factors, but mental factors too.

Important questions here include:
A) How can you prepare humans for unexpected movements?
B) How can you take account of safety in relation to human-robot interaction?

AI and learning
AI will become an important component of robot systems.
It will become technically possible to teach individual AGVs how to determine the smartest routes. Alternatively, a central AGV station could be set up with this capacity. In this case, the individual AGVs form part of an adaptive system that is controlled by this station. The station can also cross-link experiences to find solutions for new and relevant situations. The advantage of a central system for controlling AGVs is that less communication is required between the AGV and the station. The underlying systems can continue uninterrupted. It could be compared with a control system with a 'commander' (who makes strategic

decisions) and various ‘soldiers’. The system also saves a lot of energy. In fact, if it is made to work properly, this system could make individually intelligent robots superfluous. However, the question is who decides whether to build AI into above-lying systems or into individual AGVs?

4.2.4 Mistrust of AGVs in the workplace

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. The participants assumed the threats and consequences listed in Table 6 in the Bow-Tie analysis. The participants added ‘Look and feel’ themselves.

Table 6: Scenario 1: mistrust of an autonomous system

Threats	Consequences
Unclear how the autonomous system works	Less job satisfaction
Limited communication with the AGV	Verbal or physical aggression
Non-user-friendly interface	Reduced sense of safety
‘Look and feel’ integrated in the design	Work-related stress (in general)

Cause

According to the participants, mistrust of autonomous systems is founded in a fear of being replaced. The unpredictability of AGV behaviour was also cited as an important cause of mistrust.

Preventative measures in the design phase

Management must be open and transparent about their plans to implement AGV systems from the beginning. This will prevent employees becoming mistrustful and fearful of losing their jobs. Involving employees in the plans from the start will increase the support base and prevent problems during the operational phase. Including the employees more in the development process – alongside providing sufficient information and allowing them a say in decision-making about AGV designs and functionality – could increase the employees’ sense of ownership.
According to the participants, ISO 9241 provides input on how an AGV system can be built to be safe in cooperation with the end user. Optimizing AGV functions by applying user-friendly designs to user interfaces will prevent confusion about the status and intentions of the AGV. Designing routing plans in consultation with employees can help improve the support base for and acceptance of the AGV during implementation. For example, fault information and route plans could be communicated visually to employees who work with AGVs.

All AGV systems should be ergonomically designed, both physically and cognitively, and preferably be customized for each application. A user-friendly interface that displays the current activity of the AGV can contribute to situational awareness and help employees to take the right decisions in various situations.

A friendly design could help to increase the use and approachability of the AGV. A friendly design would include a curved exterior and characteristics that make the AGV more humanlike.

Noise pollution can also form a risk. The combination of AGVs in the fleet and other machinery must not exceed the maximum noise levels in a work area. Warning signals should preferably be friendly to the ear.

Preventative measures in the commissioning phase
The employees' uncertainty about the functioning of the autonomous system could be removed by applying a test protocol in the commissioning phase of the AGV system at the end user's premises. The result will be more confidence in the system.
The procedure could specify in which undesired situations the AGV can be controlled manually by the employees (decision to overrule the robot). This will allow the risks of unexpected decisions by the system to be managed.

The software algorithm can be programmed with common unpredictable human behaviour (in cooperation with engineers) or programmed to enable the AGV to recognize this behaviour and adjust its own behaviour accordingly based on a self-learning algorithm (a form of 'deep learning'). Ideally, the interface will communicate everything the AGV learns to the employee in a transparent manner. This will make the AGV more predictable and also give the human operator more control of the robot.

Preventative measures in the operational phase
Training programmes about AGVs and the risks involved in using them should be compulsory. Some system integrators even assess the results of these programmes by setting exams. Employees who complete the exam successfully receive a certificate. Interviewees also cited periodic inspections of the systems as an important risk management measure to maintain confidence in the integrity of the system. The floor manager (operations manager) or fleet manager must be able to monitor the risk management process to ensure safe interaction with the AGV in the workplace. For example, they could conduct audits and periodic management walk-arounds.

Recovery measures in the operational phase
An important way to reduce mistrust that arises following the unexpected introduction of an AGV is to familiarize the employees through immersive experience. This could be achieved by deploying serious gaming or augmented reality (AR) applications. These applications can be used to train the employees to control the AGV in a safe environment (allowing them to make errors without real consequences). This could help to prevent mistrust arising at an early stage by allowing the employees to gradually become familiarized with the workings of the system.

Any mistrust that arises from direct experience of the AGV could be discussed during performance interviews with the employees. Any input employees provide in relation to stress-reducing measures should always be taken seriously. Effective incident analyses will include these aspects of mistrust and their consequences (psychosocial workload). The workshop participants all agreed that recovery measures need to take the human factor into account and involve the HR department in the process of restoring trust and rectifying the situation.

4.2.5 Collisions between traditional machines and humans

One of the research questions concerned a comparison between a traditional machine and two autonomous systems. The two autonomous systems were a current-day AGV and an AGV of the future. Traditional machines involve a number of the same risks that apply to AGVs, whereby risks relating to the environment, the interface, the control system and operator training are important goal-oriented requirements.

Computerization is an additional threat for AGVs that is discussed in section 4.2.6 ‘Collision with an AGV’. The barriers to safe management of traditional machines (non-autonomous mobile vehicles operated by humans, such as forklift trucks, stackers, reach trucks, etc.) are summarized below in a number of goal-oriented requirements which management can apply to limit the risk of collisions.

The presence of an adequate infrastructure is an important environmental factor that should be facilitated by the organization.
For example, an important organizational risk management measure is to define work agreements and warning signals that ensure the employee is safely positioned in relation to the forklift truck. Visual and audio contact with people in the vicinity is very important while the vehicle is in motion.

The management system must continually motivate the employees to follow safe practices and inform them of the risks of vehicles.
The management needs to have clear performance goals regarding the infrastructure. Management must also ensure that its employees have the right knowledge and competencies to perform their work adequately. Management needs to find the right balance between safety and other organizational priorities. Management must also ensure that vehicles are visible at all times, are easy to drive and operate, and that users keep within the speed limits.

4.2.6 Collisions between AGVs and humans

Collisions between AGVs and humans were also discussed during the workshop.
The participants assumed the threats and consequences listed in Table 7 in the Bow-Tie analysis. The participants added IMPACT SPEED and crushing themselves.

Table 7: Scenario 2: collisions with humans

Threats	Consequences
Undesired software output	Injuries
Faulty sensor	Fatalities
Unexpected route	Emergencies and reputational damage
Wrong manoeuvre (by human or AGV)	Work-related stress
IMPACT SPEED and crushing	

Preventative measures in the design phase
A safe design is obviously an important way to prevent and limit injuries from collisions. This requires effective supply-chain and risk management to ensure that all parties are aware of the applicable legislation, regulations and risks. The following information was contributed about design measures during the workshop: Safe distances are set down in the EN 349 standard. A Kinect 3D sensor helps a vehicle to recognize humans on the route in time. The application of Redundant[60] sensors in the technical design is recommended as well.

The SLAM (Simultaneous Localization and Mapping) methodology enables the AGV to predict changes in its environment in real time and adequately respond to these before continuing its 'safe' route. Warning systems and emergency stops are required in case of slipping hazards. The workplace zoning plan should provide for specific zones that may only be entered by employees with appropriate training.

The supplier's RI&E determines the performance level (A to E)[61] of the product. The safety PLC must ensure that the AGV responds appropriately to a deviation from the normal route or activity. Programming errors can be managed by implementing an ISO standard (currently under development) that is designed to ensure software safety.

Preventative measures in the commissioning phase
Risks in the workplace such as protruding objects or falling loads must be managed by means of good housekeeping measures and pallet stacking protocols, for example. Workplace risks must be identified before the commissioning phase by means of an RI&E.

Preventative measures in the operational phase
Any changes to the AGV system must be managed by a fleet manager. The fleet manager must organize a training programme on working with AGVs for all employees. The management must make a good housekeeping protocol available to manage risks caused by leaks or obstacles on the AGV's route. An AGV will preferably have 3D or even 4D scanners to enable it to respond to unforeseen problems on uneven surfaces.

An AGV with an unlimited activity radius that is fitted with the requisite devices and software may still unexpectedly come to a standstill due to a bad manoeuvre, which can lead to accidents in an emergency situation. It is important to consider whether the emergency procedure needs to be changed to prevent this risk. Both the emergency response team and the fleet manager must be familiar with the procedure. Where AGVs are allowed in communal areas, visitors and others in these areas who are unfamiliar with the robots must be informed of the relevant house rules. The more predictable the AGV's route is for the employees, the smaller the risk that employees will display unexpected behaviour that the AGV is not equipped to respond to. It is therefore important to design the AGV system in such a way that its intended route is clearly communicated to the employees. This could include clear signals such as floor marking. There must in any case be enough room in the workplace to allow the cobot or human to move out of the way.

[60] Duplication of critical system components or functions in order to increase the reliability of the system, usually in the form of a back-up, fail-safe or system performance improvements.
[61] This is a minimum standard that applies to a specific application carried out by a robot system.

Another threat that could result in collisions or crushing is changing or handling a load in a way that is not described in the design requirements. It is important to raise awareness that changing a load (for example heavier or different products) will have consequences for safe interaction between humans and cobots. This could be described in various work instructions, for example.

The severe consequences of faulty AGV manoeuvres (that result in collisions with employees) can be demonstrated to help increase the employees' awareness of these consequences and so change their behaviour (behave more safely).

Recovery measures following collisions with humans
Recovery measures to limit the damage caused by collisions with humans depend on the quickness of the response of the responsible persons. Not only should the supplier's engineering department be available 24/7 to repair the AGV, the supplier is also responsible for ensuring that sufficient spare parts are available. In case of other risks such as a cyber-attack, users must ensure to render the rest of the system safe as soon as possible (by 'pulling the plug').

To prevent the risk of crushing during a collision, a pushback button or pull bar could be installed to enable the AGV to be moved off the crushed person. A GPS system with a warning signal will make it easier to trace the AGV in case of an incident or emergency so that first aid and emergency responders can get to the scene quickly. Employees must be able to talk freely to the HR/HSC department about the cause of incidents. AGVs could be equipped with emergency response and first aid equipment and information on how to respond in case of an emergency.

Victims and bystanders involved in severe accidents must be provided with professional support. Various forms of collision protection can be considered. For example, employees' safety boots could be strengthened with steel at ankle height (if this does not pose a risk of a broken ankle).

4.2.7 What do the workshop participants think will change if AGVs become self-learning systems (AI)?

A drawback of self-learning systems is that they can also lead to more unpredictable and complex behaviour in an AGV. The main problem for future AGVs with learning capabilities is that advanced Artificial Intelligence (AI) algorithms will no longer be testable. A solution is to implement a learning procedure in the AGV testing and development phases. This will provide a relatively controlled means of determining what behaviour the robot learns, how it learns, how it adapts over time, and what impact this has in relation to cooperation with employees.

Currently, robots are programmed to respond to their environment through linear action-reaction behaviour. In the future, self-learning algorithms will need to focus more on interpreting the intentions of humans. A study will need to be conducted of how the AGV responds (how it calculates actions and changes of direction) to various objects in its environment such as walls and moving objects. Efficiency advantages could be gained if the robots of the future are able to increase their safety and effectiveness (of their cooperation with humans) by learning from the environment without human input.

The study would identify various risk factors. However, the relationships between these factors is also important and will change with time. The outcomes of use case scenarios will need to be included in simulation programmes. These use cases can be based on training, deep learning and Virtual Reality (VR), whereby humans are included in the simulation environment. The Ministry of Defence is already doing so with autonomous robots.

5 Conclusions

The goal of this report was to identify occupational safety risks of using cobots and the relevant risk management measures. The study took the form of a literature review, interviews and a workshop. This led to answers to the following research questions:

1: *Which autonomous or semi-autonomous cobots systems currently exist and which are expected in the near future?*

2: *What are the expected or observed effects of these systems on existing occupational and process safety risks as these occur in industrial environments, and which risk management measures are in place?*

3: *To what degree can existing technologies for analysing and managing risks be applied in working environments where autonomous robot systems are used, and do additional measures need to be taken?*

The conclusions for each research question are provided below.

5.1 Which autonomous or semi-autonomous cobots systems currently exist and which are expected in the near future?

The robot industry is developing rapidly in a wide range of sectors, from healthcare to manufacturing. This also applies to cobots and AGVs, which can be distinguished from other industrial machines by the fact that they interact more with employees in the workplace. Various types of cobots and AGVs that can be used for internal logistics processes were discussed during the literature review and interviews. Appendix B contains an overview of cobots and AGVs that can be deployed for internal logistics processes. The cobots described in the appendix are not yet common in the workplace but will become so in the future. It is also expected that the systems will become more intelligent and autonomous, which will have various consequences (see also the following section).

5.2 What are the expected or observed effects of these systems on existing occupational and process safety risks as these occur in industrial environments?

Risk management of existing and new hazards relating to cobots involves various stages of the robot lifecycle, in which case various parties have a form of responsibility:
- Research and development (cobot designs and software), in which case the robot designer has a large responsibility.
- Programming (commissioning), which must be tailored to the cobots' roles and tasks in the workplace, in which case the system integrators have a large responsibility (psychosocial factors should also be studied in this stage).

- Cobot management in relation to operational processes in the workplace, in which case the employer has a large responsibility and a duty of care to ensure the safety and health of the employees.

Expected risks in relation to AGVs and cobots

The conclusion, based on the answers to research question 2, is that occupational safety risks will become more complex. The occupational risks are a consequence of the interaction between the robot, humans and the environment. An AGV can be given a degree of autonomy in certain situations, which will depend on the type of work and AI systems that affect the robot's capacity to observe, predict and respond to its environment. The AGV is facilitated by the available human and organizational capacities. In their turn – and as they grow smarter – the AGVs and cobots of the future will be better able to assist humans during human-robot-environment interactions. Table 8 below provides a list of the risks.

Table 8: Risks per lifecycle stage

Phase	Risks	Description
Design (source)	Hazardous autonomous or pre-programmed behaviour	(1) Learning involves a risk that what the AGV has learned cannot be traced. (2) Emergencies involving AGVs lead to different risks, depending on the type of emergency involved. (3) Incorrect operation of the software can cause the AGV to exhibit risky behaviour. Erroneous (unexpected) manoeuvres by AGVs can result in risks to bystanders.
	Human-Robot Interaction	(4) Learning systems take no account of human-robot interaction effects.
Design (collective)	Ergonomics	(5) Lack of clarity about an AGV's status can lead to misinterpretations by users. (6) Limited or incorrect communication by an AGV can undermine its user friendliness and may limit the user's situational awareness. (7) A non-ergonomic user interface can trigger unsafe behaviour.
	Hazardous substances Hoisting and moving	(8) The batteries used in cobots contain hazardous acids, to which engineers can be exposed. (9) If an AGV's route changes, this can result in a risk of collision.
	Psychosocial factors	(10) The unexpected introduction of AGVs in the workplace can lead to inappropriate behaviour, including vandalism.
Configuration/Introduction (collective)	Hazardous autonomous or pre-programmed behaviour	(11) If insufficient requirements have been imposed on the implementation phase, hazards may arise when a machine is commissioned. (12) The main problem with future AGVs with learning capabilities is that advanced AI algorithms will no longer be testable.
	Psychosocial factors	(13) If employees are insufficiently involved in the introduction of autonomous systems in the workplace, this can pose psychosocial workload risks and undermine their confidence in AGVs.
	Environment	(14) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees.

Phase	Risks	Description
Use (collective)	Hazardous autonomous or pre-programmed behaviour	(15) Inadequate agreements concerning when software may be modified and by whom give rise to risks in the software, which are no longer traceable. This will impact any employees working with the AGV in question. (16) A failure to verify software updates may lead to the unjustified assumption that the AGV is operating in accordance with the latest update.
	Hazardous hoisting and moving	(17) Design errors discovered during the operational phase. (18) AGVs can reduce visibility, thus posing a risk of collisions.
	Manual use	(19) Incorrect AGV start-up, in terms of log off/log on and load capacity/capacity/ratio, may pose a transport risk. (20) Unclear operational agreements about the fine tuning of AGVs (manual interventions) can be hazardous in terms of human-robot interactions.
	Environment	(21) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees. (22) Risks in the environment due to falling loads, protruding objects, or obstacles along the route may pose risks to people and to AGVs.
	Maintenance	(23) A lack of clear agreements with – or follow-up by – the supplier with regard to defects in the AGV system increases employee exposure to occupational risks. A timely and adequate response by the supplier in the event of breakdowns in the AGV system will make it possible to avoid any risk of serious incidents. (24) The absence of a key (encryption) plan within the risk management plan poses an undue risk of energy release.
	Psychosocial factors	(25) Work pressure poses risks to employee health and wellbeing (psychosocial workload).
	Accidents involving the emergency response team and the emergency procedure	(26) In the event of incidents and emergencies, appropriate recovery measures should be taken to avoid any risk of serious effects.
	Cognitive ergonomics	(27) If the language used is unclear to operators, this can lead to ambiguity and differences in interpretation.
Use (individual)	Competence	(28) If the employees responsible for maintaining AGVs are incompetent, they may engage in risky behaviour during operation and maintenance. (29) If risks are not continuously monitored and managed, there is a risk that the AGV system will no longer function reliably.
	Hazardous contact during human-robot interactions	(30) There is a risk that, if the AGV displays unpredictable behaviour, people will lose confidence in the system. This, in turn, will cause them to start anticipating unforeseen situations.

Control measures for AGVs
According to the interviewees, the principal of inherently safe design should also be applied to more autonomous systems. This should remain the focus of future development, whereby risk management should be given a more prominent role in the supply chain.

In section 3.1 it was revealed that there are many standards that can be applied to the safe design of machines and cobots. However, the social and ergonomic interaction effects of human-robot interaction remain somewhat in the shadows. There are various theories about the importance of interaction variables on human-computer interaction and human-robot interaction in the literature. These variables are also related to a number of risk management measures that were discussed during the interviews. In the interviews and during the workshop, the participants proposed that studies into the effects of MRI could be useful additions to the existing knowledge, helping to prepare employees for cooperation with cobots and AGVs and so improve the safety of the work processes.

Measures proposed by the interviewees for current working practice included physically safe applications in robot designs. However, they also discussed improving direct and indirect interaction through enhanced hardware and software interfaces and better cognitive interaction through the use of gestures, speech or audio signals to increase situational awareness and so improve safety.
Measures were also proposed to improve the design of organizational work processes in preparation for the arrival of these new robot systems. Table 9 below lists the most important risk management measures. The table distinguishes between human and cobot (with AI) environments and the relevant organizations. For a more comprehensive overview of risks and risk management measures we refer to the results of the interviews and workshops in Appendix D.

AGVs currently used in internal logistics processes do not have AI in the form of machine learning capacities. It is not possible to identify all the risks and risk management measures involved with self-learning AGVs (that are programmed with machine learning algorithms) based only on the current learning capacities of AGVs. In this respect, machine learning will lead to new challenges. Some of the interviewees predict that if semi-autonomous robots are allowed more freedom of movement, their behaviour will become more difficult to control externally. The speed of the robot’s responses will also influence the ability to control it. Humans base their trust in robots on preconceptions and experience. A misplaced excessive amount of trust (‘the robot can see me’) can lead to risky behaviour, while an unnecessary lack of trust can make it more difficult to foster acceptance of the robot in the workplace. The workshop participants confirmed the idea that humans ascribe human characteristics to robots based on their appearance and behaviour. Table 9 lists the risk management measures that were cited during the interviews and workshop.

Table 9: Overview of risk management measures for working with cobots

	Description
Design (source)	(1) Limit learning capacities. (2) Build emergency procedures into the software. (2) Coordinate emergencies involving AGVs using an RI&E and the emergency protocol. (3) Put a safety management system in place around the operating system, to safeguard the 'core safety requirements'. (4) When programming learning systems, take the human factor into account, in terms of how this affects the safety of human-robot interactions. (4) Include safety factors such as training, and a knowledge of teams and organizations in simulation programs that incorporate the human factor in the simulation environment.
Design (collective)	(5) Provide details of the significance of error categories (redundancy and advice on debugging). (5,6)Develop an interface that covers all statuses (including risk statuses) and that communicates clearly, in a way that is not open to more than one interpretation. (6) Develop a standardized (and validated) communication protocol for AGV interactions with users, to deliver an optimum user experience. (7) Make people and the environment visible in the AGV's logistic system interface. (7) Integrate innovative and ergonomic cobot applications with AGV interfaces and vice versa (comparisons could be made between different SMART pad interfaces). (8) Install the battery in a separate space from the rest of the system (separation of functions). (9) Protect programmed routes with a security password, to ensure that they cannot be modified by unauthorized users. (10) Combat vandalism by installing a camera on the AGV.
Configuration/Introduction (collective)	(11) Use a traffic light model: Does the product meet the specified procurement standards? Can inspections be visibly verified during commissioning? Has a voltage check been performed and has a verifiable training course been provided? (12) Implement the learning procedure in the AGV's testing and development phases. This will provide a relatively controlled means of determining what behaviour the robot learns, how it learns, how it adapts over time, and what impact this has in relation to cooperation with employees. (13) Involve employees in decision-making and implementation right from the start, to foster support and ownership. (13) Address aspects of distrust (psychosocial workload) about incidents in incident analyses. (14) Separate logistic flows by separating logistic areas, for example (manual work versus automated processes) or time zones (e.g. no manual procedures between 09:00 and 13:00, and interfaces between 17:00 and 22:00).
Use (collective) Use (individual)	(15) A 'Management of Change procedure' should be used to set conditions for the process by which software changes are implemented. This makes it possible to trace any changes, and to provide follow-up with regard to their impact. (16) Test the effect of software updates on different types (or versions) of AGVs, to determine the requisite universal output. (17) Supply chain management – provide feedback on lessons learned and best practices to the designer and vice versa; this can be an internal process, or it can be shared with external sector partners, to develop universally safe systems. (18) Application of sensors (including redundant sensors) in the technical design (e.g., 3D or 4D camera and sensors, an emergency shut-off, or automatic brake). (19) Clear working arrangements regarding correct AGV log off/log on in a specific area. (19) Adjusting equipment in keeping with the AGV's detection zone (e.g. the forks of a forklift truck). (20) Protocols covering responsibilities for manual use: Who is authorized to 'overrule' in given situations (other agreements apply in the event of incidents and emergencies).

	Description
	(21, 22) An environment must have enough space to enable both the AGV and people to avoid obstacles.
	(21, 22) Orderliness and tidiness procedure, including any situational factors that could be usefully monitored.
	(23) A rapid response from the engineering department (and from the supplier) to resolve any incidents with (or malfunctions of) the AGV.
	(23) In the event of a cyber-attack, the rest of the system must be made safe or rendered inoperative as soon as possible.
	(23) Effective follow-up is expedited by the efficient inventory management of perishable items (by the supplier).
	(24) The cobot can be deactivated using locks (key or codes), which cut off the power (e.g. password policy).
	(25) The AGV eliminates a rest factor for the employees. The risk of compulsive fast working could be monitored by the AGV/cobot. The AGV can then provide feedback to the operator.
	(26) A ‘push back’ button or ‘pull bar’, which ‘pushes’ the AGV back.
	(26) When it is linked to the emergency reporting system, GPS localization helps first aid and emergency responders to quickly get where they are needed.
	(27) Program (or reprogram) the AGV’s language interface to suit the user. This will help make the voice-picking system understandable to users, helping operators to interpret and control the AGV.
Use (individual)	(28) Personal certification competences: senior secondary vocational education and training (VET) professional and intellectual ability; Experience with MS Outlook; ability to understand and resolve fault codes; ability to operate 2D/3D navigation programs; interest in engineering (AGV intelligence, brake, steering, engine); risks associated with large AGVs and mobile platforms. Staff working the night shift must follow the same training courses as those on the day shift.
	(29) The appointment of a fleet operator (for AGVs) responsible for the overall management and incident management of the AGV fleet.
	(30) In the interactive design, program on the basis of human perceptions. The goal is to ensure that AGVs remain as predictable as possible.
	(30) Safety factors should be included in simulation programs, such as training, a knowledge of teams and organizations, deep learning, and Virtual Reality (VR). In this way, the human factor is introduced into the simulation environment.
	(30) Use instructional video clips to make employees aware of the risks of human-robot interaction.

5.2.1 To what degree can existing technologies for analysing and managing risks be applied in working environments where autonomous robot systems are used, and do additional measures need to be taken?

An important result revealed by the interviews is that the RI&E that companies use to identify the risks and effects of introducing AGVs in the workplace could focus more on the various lifecycle stages of the AGV. In addition to this, coordinating the various initiatives in the supply chain could lead to more integrated management of the risks in the supply chain, from the manufacture of the robot to dismantling and recycling by the customer. Changes in the working environment need to be monitored continuously in order to ascertain if the design can still be applied safely in this environment.

A risk analysis method for cobot-human systems would need to meet the following requirements:

1. The method can be applied from the start of the development process (design) all the way through to the use of the product (management).
2. The method focuses on human activities as hazard source (deviations).
3. The method takes account of the autonomy and ‘intelligence’ of the cobot (capacities).
4. The method focuses on operational hazards resulting from the planned deployment of cobots (tasks) in interaction with humans and the environment.

Based on the literature review, the HAZOP method appears to be the most suitable risk identification method for analysing robot safety. HAZOP can be applied to both the design and use (‘as built’) of robots and can also be applied to risks of non-physical or technical aspects, such as assessing procedures (such as work procedures) and complex processes (such as batch processes). The HAZOP method combines predictive research and operations research. The method focuses on identifying influences that prevent the cobot from strictly performing its functions as it was programmed to do. Finally, the method could be expanded to include a system modelling language such as UML (Unified Modelling Language) that is specifically developed to analyse the risks of human-robot interaction.

Alongside the above methods, this report also describes a framework that is based on relevant factors cited in the literature. This framework could be used as a basis for future risk analyses in the design phase, but also during the implementation of a cobot in the workplace or during the operational phase. The framework in Figure 5 could be used to measure specific factors as part of a use case.

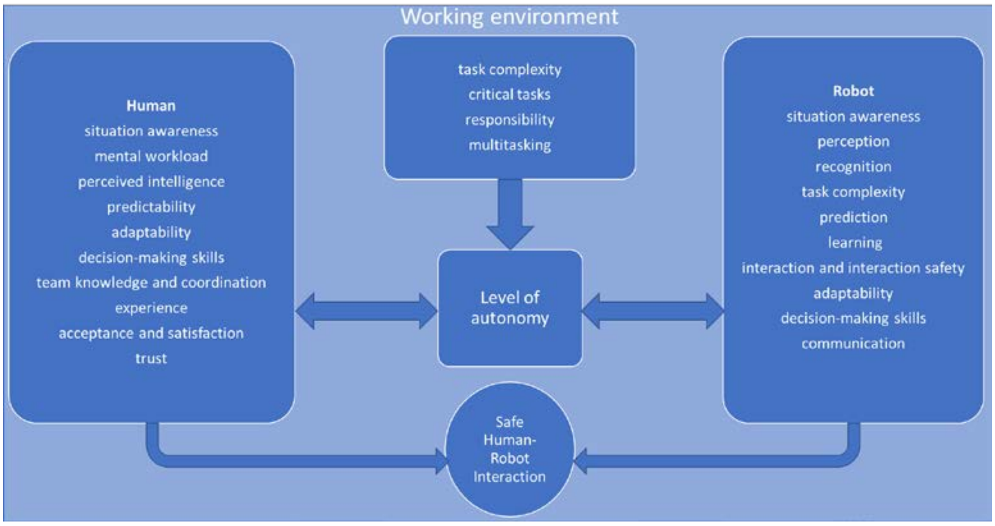

Figure 5: Factors for safe human-robot interaction

6 Discussion

AI and autonomous systems are transforming our working environment into an increasingly complex system of human, technological and organizational factors. Within this system, more and more interaction effects[62] will arise and cause-and-effect relationships and incidents will become non-linear. This will result in a completely new approach to safety philosophies and management measures[63]. Figure 6 below is based on Groeneweg (2010) and describes how safety philosophies have changed since the 1990s through a series of four paradigms. Since 2012, TNO has been developing ‘resilience strategies’ that employees and managers can apply to unexpected situations to maintain an adequate level of safety (Grotan *et al.*, 2017)[64].

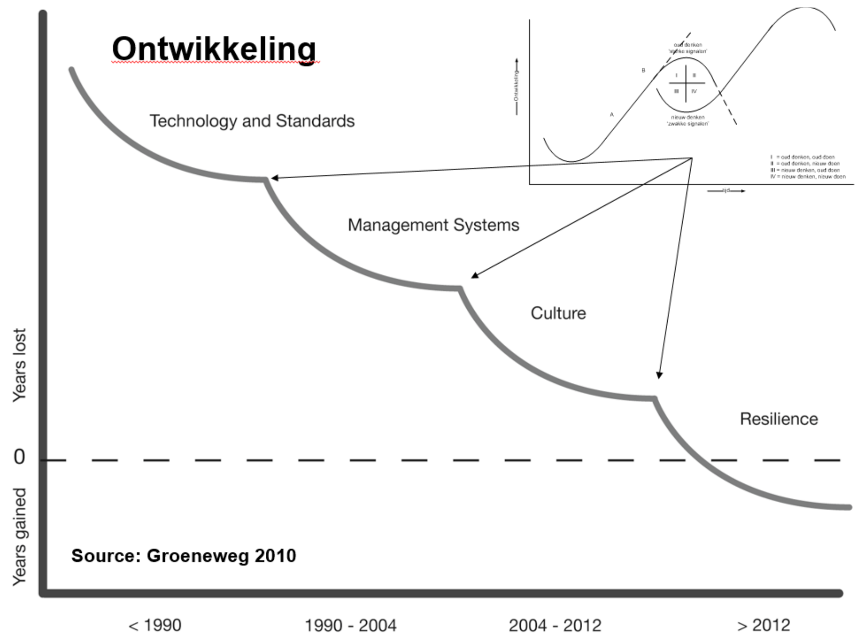

Figure 6: Developing safety paradigms

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[62] Kuhn T.S., (2012). The structure of scientific revolutions - 50th anniversary edition, University of Chicago Press, Chicago.

[63] Zwetsloot, G.I.J.M., Gallis, (2017). The need for a paradigm shift as a root cause of accidents and disasters, safety (in review).

[64] Grøtan, T. O., Wærø, I., van der Vorm, J. K. J., van der Beek, F. A., & Zuiderwijk, D. C. (2017). Using gaming and resilience engineering principles to energize a situated resilience training of front-end operators and managers. In: Walls, L., Revie, M. & T. Bedford (eds): Risk, Reliability and Safety. Innovating Theory and Practice. CRC Press. Taylor & Francis Group.

The limits of new paradigms are not easy to recognize. Kuhn (2012, p. 113) has the following to say about this: '*What a man sees depends both upon what he looks at and also upon what his previous visual-conceptual experience has taught him to see*.' This means that paradigm changes can automatically become complex processes (Kuhn, 2012).

In this case, changes in paradigms as a consequence of new digital technologies such as robotization will predominantly involve AI innovations. The complex algorithms that robots use to learn go together with hard-to-predict interaction effects between humans, technology and an organization. These complex interactions should be taken into account in the various ethical and other discussions relating to the deployment of cobots in the workplace before a cobot is purchased.

Teams of humans that collaborate with cobots will play an increasingly prominent role. Various literature delves into the composition of these teams, how they should cooperate and how they should be trained to work with cobots[65]. However, these studies were too specific in relation to the present research questions. Still, the factors involved in and effects of human-cobot teams will need to be studied more closely. This could also generate more insight into the positive effects of team collaboration on safe working relationships with cobots. Safe human-cobot teams can be ensured by implementing formal policies in organizations[66][67]. These normative rules are founded in a formal representation of the knowledge of safety-related concepts, including human aspects (such as workloads and situational awareness), robot aspects (such as situational observation) and environmental aspects (such as the distance between and approach speed of two objects). The following aspects characterize these policies:

1. Policies prescribe which actions must be carried out under specific conditions (the start and stop conditions) and facilitate proper consideration of the safety risks and the related mitigating measures. These can be generally applicable rules (such as reducing speed nearby humans) and flexible rules (such as a cobot that drives slower and emits a warning signal in corridor A because people are working there).

2. Policies have differing priorities depending on the safety risks (consequences). These policies can be learned and implemented in an organization over a period of time. Observations at work (field research) and simulations can be used to study how the system responds to the various safety risks.

[65] Gombolay, M. C., Gutierrez, R. A., Clarke, S. G., Sturla, G. F., & Shah, J. A. (2015). Decision-making authority, team efficiency and human worker satisfaction in mixed human–robot teams. Autonomous Robots, 39(3), 293-312.
[66] Neerincx, M. A., van Diggelen, J., & van Breda, L. (2016, July). Interaction design patterns for adaptive human-agent-robot teamwork in high-risk domains. In International Conference on Engineering Psychology and Cognitive Ergonomics (pp. 211-220). Springer International Publishing.
[67] Harbers, M., Aydogan, R., Jonker, C. M., & Neerincx, M. A. (2014, May). Sharing information in teams: giving up privacy or compromising on team performance? In Proceedings of the 2014 international conference on Autonomous agents and multi-agent systems (pp. 413-420). International Foundation for Autonomous Agents and Multiagent Systems.

Finally, it is also clear that in this connection, applications for digitization will increase in the future[68]. Advanced training simulation programmes facilitated by augmented reality will improve team training and can be used to test user experiences and train human-cobot teams. These technologies can be used to prepare employees for collaborating with cobots at work.

This research report sets out a preliminary framework for human-cobot interaction variables that can form the basis for the development of a human-robot interaction model to facilitate model-based risk analyses of cobot systems. By using models to realistically and accurately simulate reality, it will also be possible to make predictions in the robot design phase which can be used to test the robot software more effectively. This research also resulted in a new safety chart, based on the risks and risk management measures described in the report, that can help and inspire businesses in relation to the new risks and how to manage these when implementing cobots in the workplace.

[68] Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., & Chryssolouris, G. (2015). Design considerations for safe human-robot collaborative workplaces. *Procedia CIrP*, *37*, 248-253.

A Appendix: Protocol interviews

Introduction and opening (1 min).

1. Current context questions (10-15 min)
   a. What is your background in relation to cobots?
   b. What types of cobots (AGVs) do you work with?
   c. Which work processes at your company involve cobots/AGVs?
   d. Which cobot innovations will be most interesting for your company in the future?
   e. Which other applications of cobots are you familiar with in your industry? In which context are they used?
   f. Which applications of cobots in other sectors and/or branches are you aware of?

2. Specific characteristics and capacities of cobots/AGVs (15 min)
   a. Does the cobot work nearby an employee? (Can they touch each other?)
      - Do they carry out joint tasks? Are these tasks that they cannot complete without each other (cooperative robots)?
      - Do they have the same objectives in carrying out these tasks? Are these objectives that they cannot achieve without each other (cobotization)?

Cobot-human collaboration:
   a. Can the cobot recognize the employee and the employee's expected and unexpected behaviour (observability)?
   b. Can the cobot predict risks (including residual risks) in the situational, human and environmental context (predictability)?
   c. Can the cobot stop or adapt its work processes itself (directability)?
   d. How does the cobot influence humans, for example in order to persuade them to take a step back (directability)?
   e. How does the cobot communicate, for example by verbally or nonverbally warning a human to step back (directability)?
   f. Is the cobot self-learning (e.g. the cobot learns to take a step back because an employee needs more room to be able to work safely)?
   g. To what degree does the cobot adapt its behaviour when it is working together with humans in its direct environment? (Adaptability skill, MAR p. 202).
   h. How does the cobot influence humans in work situations where it collabortes with humans? (Interaction ability, MAR p. 205, HRI feedback).
   i. How does your cobot/AGV communicate with the user? (Interaction ability, p. 205, HRI feedback).
   j. How does the cobot/AGV recognize its environment and the objects and/or humans that participate in it? (Perception, MAR p. xx).

3. Specific characteristics and capacities of humans that work with cobots (15 min)
Employee perspective. Can humans interact with cobots?
   a. How can expected and unexpected cobot behaviour be recognized (observability)?
   b. How can the effects of risks (including residual risks) on the cobot's functioning in the situational, human and environmental context be predicted (predictability)?
   c. Can the cobot be stopped/influenced (directability)?
   d. How can humans influence cobots, for example in order to persuade them to take a step back (directability)?
   e. How can humans communicate with cobots, for example by verbally or nonverbally warning a cobot to step back (directability)?
   f. Can the cobot be reprogrammed by the employee in the workplace, for example to stop 50 cm away from the employee instead of 30 cm (autonomy)?

4. Safety of human-cobot interactions in your company (15 min)
   a) How does your company ensure safe human-robot interaction?
   b) How is the autonomy of the cobot limited (control versus self-control/leading versus following) (directability)?
   c) What are the main risks for the occupational and personal safety of the employees?
   d) How often do hazardous situations involving cobots occur in your company/sector? Are you aware of any accidents or near misses in your company or sector? Is data available on this subject?
   e) Which risk management measures are taken (e.g. technical, software, organizational, personal protective equipment)? An example could be an occupational safety strategy.
   f) Which safety measures are lacking in your opinion?
   g) What is the preferred risk management strategy/measure to manage the risks of human-cobot interactions (lifecycle approach, certification, insurance, etc.)?
   h) Are potential occupational risks of human-cobot interactions adequately communicated and reported? How could this be improved?
   i) Are there work agreements between cobots and employees based on
      - The specific deployment of the cobot in time and space, task and objective?
      - Have contexts (situational, human and environmental contexts) been defined in which a cobot may or absolutely may not collaborate (or go into failsafe mode/abort mode, for example in case of an emergency)?
      - Have only specific employees been authorized to work with the cobot?
      - Have only specific employees been authorized to work on the cobot (training, knowledge and experience)?

Closing remarks (1 min)
This was an exploratory interview. May we contact you at a later time to discuss this theme in more depth? We are considering submitting a draft version of the report to all the interviewees, so they can respond to it before we produce the final version.

We would like to thank you for participating. The final result will be a report that can help SAE to improve awareness of cobots and their risks for occupational safety. In the event this report is published, would you like us to anonymize your contribution?

I would now like to invite you to attend our workshop on 18 October. We will provide you with more information about the workshop closer to this date. You will receive a formal invitation in August.

B Appendix: Cobots and AGVs systems and internal logistics processes

In their white paper, 'Robotics in Logistics: A DPDHL Perspective on implications and use cases for the logistics industry', DHL describes a number of applications of warehouse robots and their work processes[69], which are summarized below.

1: Loading and unloading process (goods reception)

The Parcel Robot consists of a chassis, telescope, conveyor, 3D laser scanner and an artificial robot arm with gripper. The laser scanner is used to scan all parcels. An integrated computer analyses the dimensions and calculates the optimal unloading order based on this. The parcels are then placed on the conveyor. The DHL robot uses cheap cameras to localize parcels and complex software to determine the best way to stack parcels of various dimensions in order to pack the trailer in the most efficient manner without damaging any items.

2: Order-picking process

Amazon's Kiva AGV selects goods by driving an entire cart to the order picker which then selects the appropriate product. This speeds up the process considerably and saves 50% of the order-picking capacity. The SSI Schaefer Robo-Pick is a similar system developed by Knapp and Viastore.
I AM Robotics is a small company that develops one-armed AGVs that use cameras to navigate a warehouse and select products from the shelves in the same way a human would do. This system can distinguish test orders of up to forty items that it has never seen before. The picking robot TORU is a perception-driven mobile warehouse robot for intralogistics that uses 2D and 3D cameras. This technology identifies individual objects on shelves, grabs the objects and places them in the appropriate locations. TORU works alongside humans in order to ensure that objects are quickly delivered to the work or transhipment stations.

3 Packing process

Baxter, an AGV developed by Rethink Robotics, has a number of functions. Baxter is a collaborative robot that has been designed to work safely with people. Baxter's arms are made of plastic, its joints are spring-operated, and it has sensors on its arms which cause it to stop if it touches anything. A sensor in its head warns it to stop if there is a human nearby. It uses three cameras to identify objects. Employees can train the robot to perform a certain task by taking its arm and showing it what to do.

[69] Bonkenburg (2016), Robotics in Logistics: A DPDHL Perspective on implications and use cases for the logistics industry

AGV types

Definition: *An Automated Guided Vehicle (AGV) is a mobile robot that follows marks, lines, magnets or lasers to move from A to B in the workplace*[70].

An overview of AGV systems used in internal logistics processes is provided below[71]

1. Forklift and clamping AGV systems

Forklift AGV systems are used for various applications:
- transporting loads from a loading bay to a production or storage area.
- storage (narrow aisles, deep stacking, block stacking, racking).
- buffer storage.
- end-of-line applications such as receiving loads from pallet conveyors, palletizers and wrapping machines.
- loading and unloading trucks.
- transport between production and warehouse.

Clamping AGVs have clamps for handling boxes, rolls and loads that cannot be transported on pallets. Clamping AGVs can handle these loads with the same care and flexibility as forklift AGVs.

2. Very narrow aisle trucks

Very narrow aisle AGVs (VNA) are used for automated goods handling and storage in narrow warehouse aisles.

3. Automated mobile transport systems
- Automated transport systems for transporting heavy containers and large equipment (such as trains and aeroplanes).
- Warehouse AGVs that can move large stacks of pallets quickly using Omnimove technology.

4. Tractor AGVs

Tractor AGVs pull trains of carts with loads. Tractor AGVs are primarily used to transport loads between various warehouses on large industrial sites using unique multi-modal navigation technology. Automated transport using tractor AGVs increases efficiency and results in quieter traffic with less diesel trucks.

Each AGV has a pre-programmed list of stops where operators can load goods and add or remove carts from the train. The list of stops is unrestricted and can easily be reconfigured.

[70] https://en.wikipedia.org/wiki/Automated_guided_vehicle

[71] http://www.egemin-automation.nl/nl/automation/logistieke-automatisering_ha-oplossingen_agv-systemen/agv-modellen

5. Transfer AGVs

- Transfer AGVs are high-capacity vehicles designed to move loads between workstations in production environments or between production sites and warehouses.
- They communicate with pallet conveyors, end-of-line installations (palletizers, wrapping machines, robots) and automated warehouse systems (warehouse cranes) to process loads.

6. Pallet conveyors

Pallet conveyors are configured to transport and transfer pallets (wooden, with and without loads), racks, crates, rolls, containers, unit loads, etc. AGVs can also be provided with a top press to handle unstable loads, and include

- pallet conveyors (one, two or four positions on one or two levels).
- chain conveyors (one, two or four positions).
- lifting platforms.
- conveyor belts.
- shuttle systems.
- push-pull systems with stationary rolls.

C Appendix: HAZOP-UML

	Capacity cobot	Level [1-4]	Human-Robot-Interaction (oplopend in niveau)
1 directability	Level of autonomy	1	manual
		2	semi-autonomous
		3	interactive
		4	autonomous
2 observability	Level of perception (omgeving waaa	1	presense of human/object
2 observability	Level of recognition…	2	recognition human/object
		3	movement human/object
		4	movement cobot
			dangers
3 predictability	Level of predictability	1	sensorinput
	(human, object, itself)	2	based on knowledge of the environment
		3	of own movement
		4	effect of own movement
	Level of task complexity	1	simple task
		2	multiple task/action plan
		3	complex tasks
4 influencability	Level of interaction	1	intrinsic safety
	- human-cobot		basic (operator) safety
	- social interaction	2	fysical barriers
	- interaction safety		user detection
		3	workspace detection
			reactive safety
		4	dynamic safety
5 directability	Level of authonomy	1	rocognition
	(falen situatie of eigen gedrag)	2	adaptation
		3	communication
	Level of collaboration	1	set up task allocation
		2	Influence task excecution
			common goal and strategy decision
		3	adjust behavior cobot based on direct feed back
		4	adjust behavior cobot based on observation
6 learning	Level of learning (cobot)	1	informing
			moving
		2	recognise dangers
		3	anticipate
		4	anticipate and communicate

	Node nummer:	1.0							
	Task	stocking shelves							
nr.	deviation	cause	consequences		controls	beoordeling			aktie
	(guidance/keywords)	(scenario)	(use case effect)	(real world effect, dangers)	(system reactions / HRI)	Kans	Effect	Risico	(verplicht indien hoog risico)
1	not - fully autonomous	control fails	- cobot does not respond to command - cobot is uncontrollable	- cobot filling arm hits man - 1 person heavily injured	fail safe design emergency stop button	2	4	8	place an extra sensor on cobot filling arm
		no power	- cobot stop movement - stay still	- cobot blocks path - nuisance for the environment - collision	malfunction light on cobot	3	1	3	
2	faster/slower- fully autonomous	control fails	cobot arm goes faster than intended	- cobot filling armhits human hwith high speed - fatality	...	2	5	10	include in manual
		wrong setting		....	...				
7	as well as- movement of man / object	misinterpretation of cobot about movement of human	cobot makes unexpected movement	cobot-arm hits human	...				personal protection (PBM)

D Appendix: Results of the interviews and workshop

A summary of the results of the interviews and the workshop is provided here. The first table provides an overview of the occupational risks by product lifecycle phase. The second table describes the risk management measures cited by the participants. These risks are ordered based on the risks described in the first table.

	Risks	Description
Design	Hazardous autonomous or pre-programmed behaviour	(1) Learning involves a risk that what the AGV has learned cannot be traced. (2) Emergencies involving AGVs lead to different risks, depending on the type of emergency involved. (3) Incorrect operation of the software can cause the AGV to exhibit risky behaviour. Erroneous (unexpected) manoeuvres by AGVs can result in risks to bystanders.
	Human-Robot Interaction	(4) Learning systems take no account of human-robot interaction effects.
Design (collective)	Ergonomics	(5) Lack of clarity about an AGV's status can lead to misinterpretations by users. (6) Limited or incorrect communication by an AGV can undermine its user friendliness, and may limit the user's situational awareness. (7) A non-ergonomic user interface can trigger unsafe behaviour.
	Hazardous substances	(8) The batteries used in cobots contain hazardous acids, to which engineers can be exposed.
	Hoisting and moving	(9) If an AGV's route changes, this can result in a risk of collision.
	Psychosocial factors	(10) The unexpected introduction of AGVs into the workplace can lead to inappropriate behaviour, including vandalism.
Configuration/Introduc	Hazardous autonomous or pre-programmed behaviour	(11) If insufficient requirements have been imposed on the implementation phase, hazards may arise when a machine is commissioned. (12) The main problem for future AGVs with learning capabilities is that advanced Artificial Intelligence (AI) algorithms will no longer be testable.
	Psychosocial factors	(13) If employees are insufficiently involved in the introduction of autonomous systems in the workplace, this can pose psychosocial workload risks and undermine their confidence in AGVs.
	Environment	(14) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees.
Use (collective)	Hazardous autonomous or pre-programmed behaviour	(15) Inadequate agreements concerning when software may be modified and by whom give rise to risks in the software, which are no longer traceable. This will impact any employees working with the AGV in question. (16) A failure to verify software updates may lead to the unjustified assumption that the AGV is operating in accordance with the latest update.
	Hazardous hoisting and moving	(17) Recovery measures in the operational phase. (18) AGVs can reduce visibility, thus posing a risk of collisions.

	Risks	Description
	Manual use	(19) Incorrect AGV start-up, in terms of log off/log on and load capacity/capacity/ratio, may pose a transport risk. (20) Unclear operational agreements about the fine tuning of AGVs (manual interventions) can be hazardous in terms of human-robot interactions.
	Environment	(21) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees. (22) Risks in the environment due to falling loads, protruding objects, or obstacles along the route may pose risks to people and to AGVs.
	Maintenance	(23) A lack of clear agreements with – or follow-up by – the supplier with regard to defects in the AGV system increases employee exposure to occupational risks. A timely and adequate response by the supplier in the event of breakdowns in the AGV system will make it possible to avoid any risk of serious incidents. (24) The absence of a key (encryption) plan within the risk management plan poses an undue risk of energy release.
	Psychosocial factors	(25) Work pressure poses risks to employee health and wellbeing (psychosocial workload).
	Accidents involving the emergency response team and the emergency procedure	(26) In the event of incidents and emergencies, appropriate recovery measures should be taken to avoid any risk of serious effects.
	Cognitive ergonomics	(27) If the language used is unclear to operators, this can lead to ambiguity and differences in interpretation.
Use (individual)	Competence	(28) If the employees responsible for maintaining AGVs are incompetent, they may engage in risky behaviour during operation and maintenance. (29) If risks are not continuously monitored and managed, there is a risk that the AGV system will no longer function reliably.
	Hazardous contact during human-robot interactions	(30) There is a risk that, if the AGV displays unpredictable behaviour, people will lose confidence in the system. This, in turn, will cause them to start anticipating unforeseen situations.

Description of the risks	Description of the risk management measure
(1) Learning involves a risk that what the AGV has learned cannot be traced.	(1) Limit learning capacities.
(2) Emergencies involving AGVs lead to different risks, depending on the type of emergency involved.	(2) Build emergency procedures into the software. (2) Coordinate emergencies involving AGVs using an RI&E and the emergency protocol.
(3) AGV safety cannot always be guaranteed by the software.	(3) Put a safety management system in place around the operating system, to safeguard the ‘core safety requirements’.
(4) Learning systems take no account of human-robot interaction effects.	(4) When programming learning systems, take the human factor into account, in terms of how this affects the safety of human-robot interactions. (4) Include safety factors such as training, and a knowledge of teams and organizations in simulation programs that incorporate the human factor into the simulation environment. (4) Include safety factors in simulation programs, such as training, a knowledge of teams and organizations and Virtual Reality (VR).
(5) Lack of clarity about an AGV’s status can lead to misinterpretations by users.	(5) Develop an interface that covers all statuses (including risk statuses) and that communicates clearly, in a way that is not open to more than one interpretation. (5) The AGV should retain its current status (fault code) until the operator has confirmed it.
(6) Limited or incorrect communication by an AGV can undermine its user friendliness, and may limit the user’s situational awareness.	(5) Provide details of the significance of error categories (redundancy and advice on debugging). (6) Develop a standardized (and validated) communication protocol for AGV interactions with users, to deliver an optimum user experience.
(7) A non-ergonomic user interface can trigger unsafe behaviour.	(7) Make people and the environment visible in the AGV’s logistic system interface. (7) Integrate innovative, ergonomic, cobot applications with AGV interfaces and vice versa (comparisons could be made between different SMART pad interfaces).
(8) The batteries used in cobots contain hazardous acids, to which engineers can be exposed.	(8) Install the battery in a separate space from the rest of the system (separation of functions).
(9) If an AGV’s route changes, this can result in a risk of collision.	(9) Protect programmed routes with a security password, to ensure that they cannot be modified by unauthorized users.
(10) The unexpected introduction of AGVs into the workplace can lead to inappropriate behaviour, including vandalism.	(10) Combat vandalism by installing a camera on the AGV.

Description of the risks	Description of the risk management measure
(11) If insufficient requirements have been imposed on the implementation phase, hazards may arise when a machine is commissioned.	(11) Use a traffic light model: Does the product meet the specified procurement standards? Is the commissioning certificate visible? Has a voltage check been performed and has a verifiable training course been provided?
(12) The main problem for future AGVs with learning capabilities is that advanced Artificial Intelligence (AI) algorithms will no longer be testable.	(12) Implement the learning procedure in the AGV's testing and development phases. This will provide a relatively controlled means of determining what behaviour the robot learns, how it learns, how it adapts over time, and what impact this has in relation to cooperation with employees.
(13) If employees are insufficiently involved in the introduction of autonomous systems in the workplace, this can pose psychosocial workload risks.	(13) Involve employees in decision-making and implementation right from the start to foster support and ownership. Trust in autonomous systems can be increased by: – Verbal communication by the AGV (based on voice recognition of persons known to the AGV). – Develop a safe AGV system together with the user based on ISO 9241. Apply a test protocol during the configuration phase. Use a human-focused interaction design in which faults and routes are clearly communicated. – Clearly communicate the options for manual control of the AGV is specific situations. – Design a route plan for the AGV in consultation with the employees. – The software algorithm can be programmed with common unpredictable human behaviour (in cooperation with engineers) or programmed to enable the AGV to recognize this behaviour and adjust its own behaviour accordingly based on a self-learning algorithm (a form of 'deep learning'). – A friendly and 'cuddly' design could help to increase trust in the AGV. – Give employees time to get used to the AGV. Periodic inspections of the systems increases the technical reliability of the system and hence the confidence in it. – During performance interviews, take the comments of the employees about stress-reducing measures seriously. – Deploy serious gaming or augmented reality (AR) applications to familiarize the employees with the AGV. – Address aspects of distrust (psychosocial workload) about incidents in incident analyses.
(14) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees.	(14) Separate logistic flows by separating logistic areas, for example (manual work versus automated processes) or time zones (e.g. no manual procedures between 09:00 and 13:00, and interfaces between 17:00 and 22:00). (14) Orderliness and tidiness procedure (housekeeping), including any situational factors that could be usefully monitored. (14) Validated navigation software, including SLAM (Simultaneous Localisation And Mapping), enables the AGV to predict changes in its environment in real time and adequately respond to these and plan a 'safe' route. (14) The use of safety mats is an alternative to bystander detection.

Description of the risks	Description of the risk management measure
	(14) An ergonomic interaction design will help.
(15) Inadequate agreements concerning when software may be modified and by whom gives rise to risks in the software, which are no longer traceable. This will impact any employees working with the AGV in question.	(15) A ‘Management of Change’ procedure should be used to set conditions for the process by which software changes are implemented. This makes it possible to trace any changes, and to provide follow-up with regard to their impact.
(16) A failure to verify software updates may lead to the unjustified assumption that the AGV is operating in accordance with the latest update.	(16) Test the effect of software updates on different types (or versions) of AGVs, to determine the requisite universal output.
(17) Hazardous contact caused by design faults in the operational phase.	(17) Supply chain management – provide feedback on lessons learned and best practices to the designer and vice versa; this can be an internal process or it can be shared with external sector partners, to develop universally safe systems. (17) Legislation and regulations on risk management should be discussed in the supply chain to manage the risk as much as possible. (17) Apply the EN 349 standard for safe distances.
(18) AGVs can reduce visibility, thus posing a risk of collisions.	(18) The application of Redundant sensors in the technical design is recommended. (18) 3D and 4D cameras and sensors.
(19) AGVs can reduce visibility, thus posing a risk of collisions.	(19) The application of Redundant sensors in the technical design is recommended. (19) Warnings and emergency stops in case of slipping hazards. (19) An emergency stop. (19) Assessment of power based on torque. (19) Lidar, laser scanner and safety mats. (19) Programmable Logic Controller (PLC). (19) Communication using audio signals. (19) Emergency brakes (for heavy AGVs) and reliable pressure cylinders. (19) 3D and 4D cameras and sensors that detect humans on the route. (19) Alarms.
(20) Incorrect AGV start-up, in terms of log off/log on and load capacity/capacity/ratio, may pose a transport risk.	(20) Clear working arrangements regarding correct AGV log off/log on in a specific area. (20) Adjusting equipment in keeping with the AGV’s detection zone (e.g. the forks of a forklift truck). (20) Keep the AGV’s route free of obstacles (fleet management). (20) Emergency stop buttons on all sides to allow fast control.

Description of the risks	Description of the risk management measure
(21) Unclear operational agreements about the fine tuning of AGVs (manual interventions) can be hazardous in terms of human-robot interactions.	(21) Protocols for manual use. Who has the authority to overrule the AGV? Alternative rules in case of emergencies. (21) Trained fleet managers can be made responsible for monitoring changes to the AGV system (e.g. software changes).
(22) If there are too many hazards in the environment, the risk of information being missed by people or by an AGV increases the risks to employees. Risks in the environment due to falling loads or protruding objects may pose risks for human-AGV interaction. Obstacles or hydraulic oil on the route can cause a slipping hazard.	(21, 22) An environment must have enough space to enable both the AGV and people to avoid obstacles. (21, 22) Orderliness and tidiness procedure (housekeeping), including any situational factors that could be usefully monitored. (22) An environment must have enough space to enable both the AGV and people to avoid obstacles. (22) Orderliness and tidiness procedure (housekeeping), including any situational factors that could be usefully monitored.
(23) A lack of clear agreements with – or follow-up by – the supplier with regard to defects in the AGV system increases employee exposure to occupational risks. A timely and adequate response by the supplier in the event of breakdowns in the AGV system will make it possible to avoid any risk of serious incidents.	(23) A rapid response from the engineering department (and from the supplier) to resolve any incidents with (or malfunctions of) the AGV. (24) In the event of a cyber attack, the rest of the system must be made safe or rendered inoperative as soon as possible. (23) Effective follow-up is expedited by the efficient inventory management of perishable items (by the supplier).
(24) The absence of a key (encryption) plan within the risk management plan poses an undue risk of energy release.	(24) The cobot can be deactivated using locks (key or codes), which cut off the power. (24) Include a password management policy in the risk management plan.
(25) Work pressure poses risks to employee health and wellbeing (psychosocial workload).	(25) The AGV eliminates a rest factor for the employees. The risk of compulsive fast working could be monitored by the AGV/cobot. The AGV can then provide feedback to the operator.
(26) In the event of incidents and emergencies, appropriate recovery measures should be taken to avoid any risk of serious effects.	(26) A ‘push back’ button or ‘pull bar’, which ‘pushes’ the AGV back. (26) When it is linked to the emergency reporting system, GPS localization helps first aid and emergency responders to quickly get where they are needed. (26) AGVs could be equipped with emergency response and first aid equipment for faster emergency response. (26) Employees must be able to talk freely to the HR department about incidents in case of physical injury or a severe fall in trust.
(27) If the language used is unclear to operators, this can lead to ambiguity and differences in interpretation.	(27) Program (or reprogram) the AGV’s language interface to suit the user. This will help make the voice-picking system understandable to users, helping operators to interpret and control the AGV. (27) The user manual must be written in the customer’s national language.

Description of the risks	Description of the risk management measure
(28) If the employees responsible for maintaining AGVs are incompetent, they may engage in risky behaviour during operation and maintenance. There is a higher likelihood of inappropriate use during the nightshift. This shift is sometimes undermanned, which leads to less attention being paid to safety conditions.	(28) Personal certification competences: senior secondary vocational education and training (VET) professional and intellectual ability; experience with MS Outlook; ability to understand and resolve fault codes; ability to operate 2D/3D navigation programs; interest in engineering (AGV intelligence, brake, steering, engine); risks associated with large AGVs and mobile platforms. Staff working the night shift must follow the same training courses as those on the day shift.
(29) If risks are not continuously monitored and managed, there is a risk that the AGV system will no longer function reliably.	(29) The appointment of a fleet operator (for AGVs) responsible for: – the continuous operation of the fleet – resolving issues in case of stagnation (incident management) – employee training – collective measures (AGV zoning and demarcation in relation to other employees or third parties). – familiarizing themselves with general organizational rules and codes of behaviour and sharing these with the employees.
(30) There is a risk that, if the AGV displays unpredictable behaviour, people will lose confidence in the system. This, in turn, will cause them to start anticipating unforeseen situations.	(30) In the interactive design, program on the basis of human perceptions. (30) The goal is to ensure that AGVs remain as predictable as possible. (30) Safety factors should be included in simulation programs, such as training, a knowledge of teams and organizations, deep learning, and Virtual Reality (VR), whereby humans are included in the simulation environment. (30) Use instructional video clips that illustrate the consequences (of a collision) to make employees aware of the risks of human-robot interaction.

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