ADVANCED ROBOTIC SYSTEMS FOR INSPECTION AND MAINTENANCE OF GAS AND OIL INFRASTRUCTURE (ID10)

1 Introduction

Automating tasks through technological advancements has been an ongoing process in many industries. This development can also significantly impact occupational safety and health (OSH) in a work environment. It enables the removal of workers from hazardous situations and can improve the quality of work. This can be accomplished by automating cognitively strenuous tasks using an artificial intelligence (AI)-based system or by 'delegating' repetitive tasks to accurate and tireless machines like intelligent robotic systems. Some tasks might not be fully automated, but workers can still receive support through, for example, collaborative robots (cobots) operating in a shared space with workers. An increasing number of companies employ AI or advanced robotics. Although still in their infancy in terms of deployment, AI-based systems for the automation of both cognitive and physical tasks, as well as intelligent cobots, show promise in a variety of sectors. However, more information is needed on how they are implemented and managed in the workplace to help ensure workers' safety and health in present as well as in future applications.

EU-OSHA has developed a number of case studies with the aim of investigating the practical implementation of AI-based systems for the automation of physical and cognitive tasks and of intelligent cobots in the workplace, their impact on workers, how OSH is managed in relation to such systems, and to gain a better understanding of the drivers, barriers and success factors for the safe and effective implementation of these systems.

To develop these case studies, several key informants at the EU and international levels, such as workers' representatives and industry associations representing the targeted sectors, were consulted. Initially, 16 cases were identified and preliminary information was collected through a questionnaire. Hereafter, 11 of them were further developed into case studies, including higher levels of information collected at the workplace level.

2 Methodology

The primary data source for the case studies was interviews held with different stakeholders within companies. For each case study, up to five interviews were conducted with workers of the company from different work areas. The participants included operators, data protection officers, health and safety engineers, managers work-councillors and technology officers.

The interviews had a duration of 1-1.5 hours each and were performed in the participants' native language, if possible, or alternatively in English. The interviews were conducted using an interview guide, while the results of the interviews were anonymised.

3 General company description

The Norwegian gas infrastructure company used in this study is an operator for integrated systems for transporting gas from the Norwegian continental region to other European countries and the United Kingdom. Their objective is **safe and reliable gas transport**. They are state-owned and were founded in 2001. Currently, they have over 350 workers. They heavily focus on value-driven business conduct towards their customers, partners and workers. Their core values lie in **ethical, sustainable and socially responsible business conduct** as well as a strong internal focus on the **personal development of their workers**. The expertise of their workers is described as a fundamental requirement for the safety and reliability of their operation. They see the personal and professional development of their workforce as an important goal to further and aim to support talent within their company. They also created a specialised unit focusing on safety, security and sustainability towards the environment but also towards their workers' workspaces. Duties of this unit include risk assessments and management, emergency preparations, the monitoring of OSH laws and governing documents, and regarding all points: continuous improvement.

As they are government-owned, the Norwegian government sets their operation framework. They operate pursuant to the **Norwegian Petroleum Activities Act** and in close collaboration and agreement with the gas transport system owners. This also includes maintenance of current and future developments of gas infrastructure. An integral part in fulfilling this mission is the maintenance of a reliable and safe gas transportation infrastructure. Specialists have previously performed the inspection process manually by entering and inspecting the gas tanks themselves. This work is both straining and dangerous; hence, they turned to robotic and AI-based solutions to automate this task.

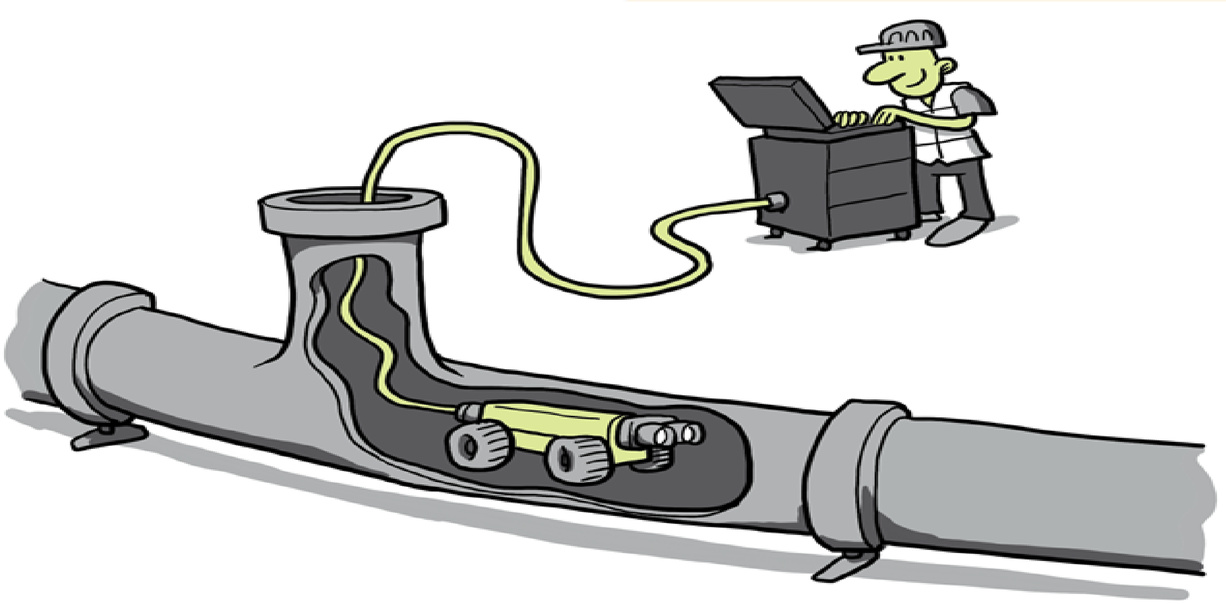
3.1 Description of the system

The company utilises two robotic systems to assist in the inspection and maintenance of the gas and oil infrastructure. A vital part of this is the external and internal inspection of equipment and assets in oil and gas facilities — specifically, **the inspection of pressure tanks for any damages, material wear or other need for intervention**. Previously, a trained inspector had to enter the tanks to perform the inspection. Now, they **developed two kinds of robotic systems** to perform this task. The first one is a **four-meter-long extendable, flexible robotic arm with a borescope and light fixtures attached to the front**. The robot can also be equipped with an ultrasound probe to inspect wall thickness. It can be operated manually to inspect pressure tanks from within and provide an overview of the state of the vessel. The **second is a robotic crawler system with magnetic wheels to go into pressure tanks, to perform the needed check-ups in narrow spaces, deeper spaces or anywhere a detailed inspection of an area is needed**. For this, the operator stands outside the vessel. The advanced robot's magnetised wheels allow it to drive along the tubular walls of the tank at 360°, inspecting all possible damages close-up. Based on a 3D model and map, a path for the robot is generated by the operators, which it follows through the tank. However, it can also be operated manually, for example, for spot inspections. Both robotic systems either **record or transmit their findings to the operators outside**, who can control the robotic system inside the confined area. After their inspections, **they autogenerate a report for the inspectors**, who then perform additional analysis if and where repairs are needed. With the help of these two advanced robots, areas with a need for intervention are identified, while operators rarely have to enter the pressure vessels themselves. Currently, **repair work on the identified areas is still performed manually**. However, **the time a human worker spends inside the vessels has been cut down significantly**.

The company **worked together with robotic development teams and other stakeholders** to create these two solutions with a unique fit to their case study. Factors like minimum length of the robotic arm to reach the necessary depth in the tanks or size of the robotic crawler to inspect narrower tubes could already be factored in during the design process. So far, testing and operations with the systems has been without incident.

A cartoon-style representation of the system, performed tasks and interaction with workers, including some of the challenges and opportunities for OSH is presented in Figure 1

Figure 1. Advanced robotic systems for inspection and maintenance of gas and oil infrastructure

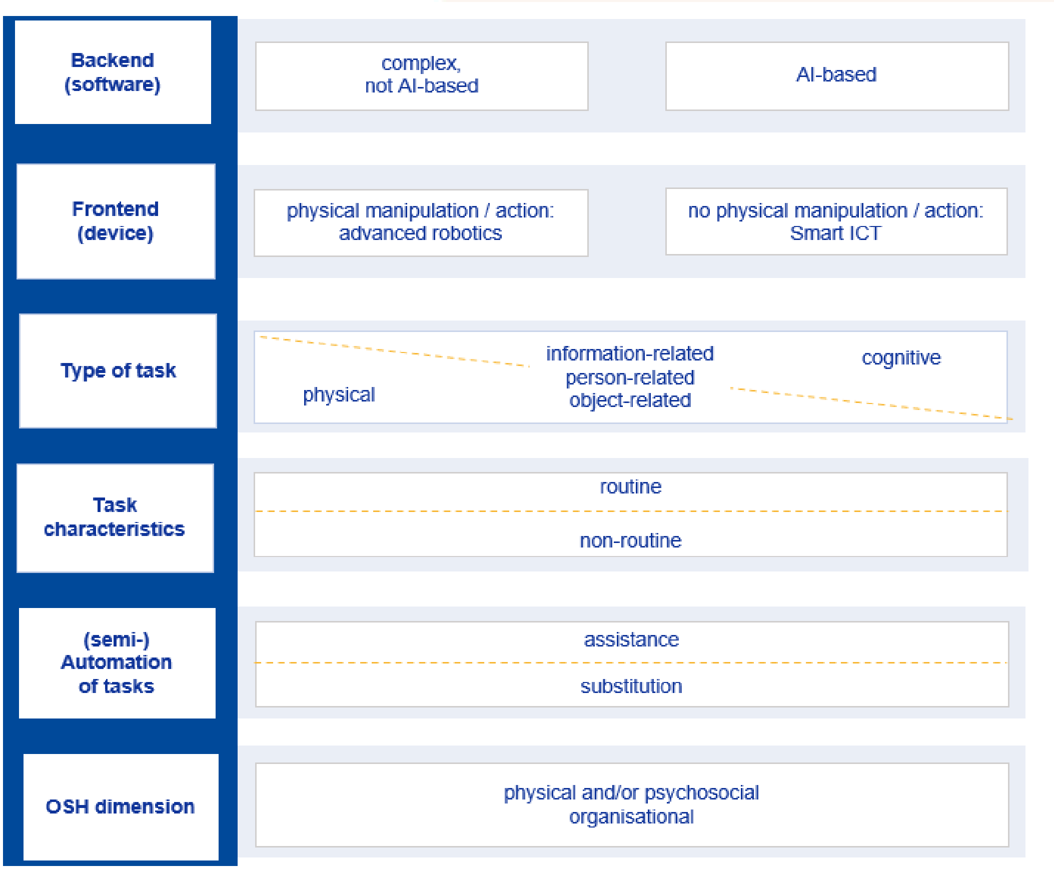


3.2 Taxonomy-based categorisation

To categorise different types of technology, a taxonomy specific for different important criteria of AI-based systems and advanced robotics was developed by EU-OSHA.[1] This taxonomy includes what type of backend and frontend is being used and the type of task performed, as well as which category it falls under (information-related, person-related or object-related). It distinguishes between routine and non-routine task characteristics as well as the degree of automation in the form of assistance or substitution. Finally, the taxonomy takes into account different OSH dimensions (physical, psychosocial and/or organisational) that are impacted by the technology.

Both robotic solutions were developed to reduce the time workers have to spend in the gas tanks to inspect them. Hence, both robotic systems are performing primarily a **physical task**, which is the physical entering of the gas vessels. The camera or borescope records or transmits images from inside the tank to a team of operators outside. The whole system is based on a **complex but deterministic** backend software. It performs a **physical, object-related** manipulation, while being controlled by an external operator. This falls under the category of labour **substitution**, as the robot primarily performs the physical part of the inspection task. The autogenerated report is currently **not AI-based** and provides additional **support** to the **cognitive** part of the inspection task. However, a trained inspector still has to evaluate the material and has final decision authority. OSH implications described by the company focus on **physical benefit** factors, which are described in detail below.

Figure 2: Taxonomy for AI-based systems and advanced robotics for the automation of tasks



Workers tasked with the inspection of the gas vessels are highly skilled technical engineers. The task they perform carries significant responsibility and needs extensive training and experience to be performed at a sufficient level.

[1] EU-OSHA – European Agency for Safety and Health at Work, *Advanced robotics, artificial intelligence and the automation of tasks: definitions, uses, policies and strategies and Occupational Safety and Health*, 2022. Available at: https://osha.europa.eu/en/publications/advanced-robotics-artificial-intelligence-and-automation-tasks-definitions-uses-policies-and-strategies-and-occupational-safety-and-health

The impact on the **routine for workers is significant, while the job content remains comparatively consistent**. The workplace of the operators has changed drastically, while their primary task in context of tank inspection has not. Previously, **inspections were taking place inside the gas tanks, in safety gear**. **The inspectors are now situated outside the gas tank in a temporary operating station.** A significant part of their routine regarding inspection has become largely redundant. Steps taken to prepare the inspection have changed as well. Inspectors do not need to put on the safety equipment and protective gear to inspect the tanks; instead, they need to set up a temporary workplace outside the inspection site. This temporary workstation contains the technological equipment needed to operate the robots. Previously, the tanks had to be separated into individual components to allow inspection from the inside. With the robotic systems, very few parts need to be removed to grant them entry. However, all skill and knowledge needed for proper and safe disassembly need to be maintained, as the disassembly still needs to happen if defects in the tanks are spotted. The inspectors' primary tasks remain largely unchanged. They still perform the inspection, just remotely. It still needs a qualified, trained worker to assess any findings made with the robotic systems. However, the analysis of the vessel's inside state is now also supported by an initial report produced by the robots.

Regarding the job content of inspectors, while it has not changed as much as their routine, it has expanded. **They needed to acquire skills to operate both robotic systems.** Controlling the robotic arm properly is important to gain images of the tank's inside at a sufficient quality. Also, planning a path for the crawler, operating it manually and learning to interpret its report are new skills that previously were not part of the job. These new skills and subsequent task all expand the inspectors' skill portfolio.

4 Implementation process

A key factor for the successful integration of technology into a new work environment is the implementation process. Several factors, such as the identification of objectives and goals prior to implementing the technology, design decisions and participation, worker involvement and training, as well as the inclusion of guidelines or legislation, can influence it. In addition, some of the most important steps are the assessment of whether the intended goals have been reached, documentation of what challenges were faced, and finally consideration of how these lessons influence future company plans regarding the implementation of either new systems or more of those already implemented.

4.1 Motivators and goals

Setting **goals** prior to implementing a technology can help quantify the success of the implementation and also inform what kind of technology is needed to reach them. The interviewees expressed a number of objectives and goals for the introduction of the two advanced robotic systems. They name health, safety and environment, or HSE, as one of their most significant drivers for implementing these technologies.

The primary motivator was **worker safety**. Any worker inside a pressure vessel is exposed to numerous hazards. Workers tasked with detaching and reattaching the vessel parts were exposed to residual physical risks from working outside and possibly in high places. More importantly, workers tasked with inspecting the vessels from the inside ran significant risks. **Working inside a pressure vessel coincides with several workplace hazards.** The inspector would have to enter confined spaces and encounter chemical hazards as the pressure tanks were filled with gas and ergonomic hazards due to changing light conditions and possibly poor posture for long periods of time. If a worker is to enter a tank, they wear protective gear in the form of a helmet, gloves, breathing masks, a safety suit and a security harness. The vessels also do not all provide straight ground to walk on, which leads to possible tripping hazards. Overall, the company was interested in increasing their workers' safety by introducing robotic solutions and removing them from hazardous environments as much as possible.

Another goal was to consider **efficiency**. The inspection process used to be time consuming and needed many resources. Manually, **the process takes around three days per vessel**. During this time, the inspectors and additional workers are outside performing the attachment and reattachment task. Taking the tanks apart for inspection also contributed to material wear. Every attachment and detachment can affect the material of pipes and contribute to wear. Finding a robotic solution not only made the process faster, it also reduced said strain on the material.

4.2 Implementation

Before a new technology can be introduced to a workplace there are a variety of factors to consider and often several stakeholders to involve. The implementation process can differ from company to company. With AI-based systems and advanced robotics being so customisable in their application, the general implementation is going to be different for each case study. Nonetheless, there can be common implementation steps taken with regard to who is involved in the process. The standards considered to implement a technology are equally important, both with regard to which are widely used and which are relevant to a specific case study.

Furthermore, the individual difficulties and challenges are as vital to understanding the success of a case study as the ones more broadly shared among several case studies.

4.2.1 Implementation steps

The implementation steps were **largely dependent on the collaboration with several other stakeholders during the design process**. The gas infrastructure operator was aware of the working situation during vessel inspection, as well as how time consuming this task is. Hence, they reached out to several collaborators to create the two systems. For one, this was a robotic development specialist, which adapted a previously existing robotic crawler to their needs. Another set of collaborators tackled the problem of visual quality and 3D modelling on the software end. The robotic arm went through several design cycles, as factors like optimal length needed to be determined. This also included in-field testing and continuous collecting of feedback from the end users. This feedback goes directly to the developers and is integrated as needed. There are still new features being developed and tested to improve the robots' performance. **The ownership of the robotic systems remains with the developers, even when employed at the gas infrastructure operator's worksite.**

Before the robots are used at a worksite, a risk assessment is performed at that location.

The two robots are mobile and transportable to whichever worksite they are needed at. This set their implementation apart from traditional production lines, for example, where a stationary robotic system is integrated. The robots were developed in such a way as to be used in the gas vessels' environment, without the need to change it.

4.2.2 Standards and regulations

Both robotic systems comply with EU and Norwegian safety standards for robotic systems. During the development of the robotic system, several European standards for creating robotic systems as well as technology fit to work in a gas vessel needed to be considered. One major consideration was the feasibility of creating an ATEX-certified robotic solution. ATEX stands for the French 'Atmosphères Explosives' and is colloquially used to refer to the **ATEX 2014/34/EU**. The directive includes guidelines in the field of explosion protection, namely the ATEX product guideline 2014/34/EU and the ATEX company guideline 1999/92/EG.[2] The robotic crawler is not ATEX-certified due to technological limitations, however, additional safety measures were taken that make the robot safe to use in the environment of a gas vessel. Namely, additional gas detectors were installed that force a system shut down when atmospheric gas levels become too saturated. In addition to that, they also consulted publications by third parties. The sprint robotics roadmap and white paper on exposure are highlighted as well is their guideline for the implementation of robotics.

4.2.3 Difficulties and challenges during the implementation

The largest difficulty was creating a robotic system capable of performing the task at hand. While this was not a difficulty during the implementation, but more during the design process, it was a time-consuming challenge. Finally, the company worked together with a third-party robotics development team and other stakeholders **to create not one but two robotic systems capable of assisting in the task**.

It is easy to see how one assumes that it should take one robotic system to automate a task previously performed by one worker. And given the increasing capabilities and flexibilities of robotic systems, it is easy to assume one system will be capable of fully automating the task. However, these tasks are performed by highly skilled workers and contain many complex subtasks. Acknowledging that several systems might be needed to achieve a sufficient result is an important step in the implementation process.

However, collaborating with several developers on the two robotic systems independently also proved to be a challenge. This increased the need for and complexity of communication, as each company signed confidentiality agreements. However, while having different developers and stakeholders involved came with its own set of difficulties, overall, the benefits outweighed them from this case study's point of view.

Another difficulty that arose during the implementation phase was the **COVID-19 pandemic**. It slowed down the process significantly and made collaboration between the involved parties more difficult, especially when situated in different countries.

Another challenge encountered during the implementation of the systems was **fear of job loss** by the inspectors. This led to an intervention by management where they showed that this workplace change is in the operators' favour and makes it safer and healthier. This countermeasure has resulted in acceptance for the systems growing. Nonetheless, the gas infrastructure operator is aware that fear of job loss will likely be encountered again and again, as automation of the worksites continues.

[2] See: https://ec.europa.eu/docsroom/documents/52195

4.3 Worker involvement

Involving the end user in the development of a new technology can help developers create technology that is suited to their wishes and needs. This case study arose from a collaboration of different stakeholders, including the gas infrastructure operator as the initiator and primary end user. The input of the vessel inspectors was vital to the technology development process. The gas infrastructure operator created the two robotic solutions in cooperation with several partners, including a specialised robotic company. This way, workers could already contribute at the design phase, to help create two robotic systems capable of performing the task at hand.

4.3.1 Training and worker qualifications

Worker training and education is a major element for the success of technology implementation.[3,4] Workers needed to undergo training, to use the robotic arm and crawler. Beyond learning how to manually operate the system, or in the case of the crawler, create a path for it to follow through the vessel, the inspectors also had to learn how to read the output the systems provide. The robotic crawler specifically creates a report of the vessel state, which was previously done by the worker manually. The report complies with the company's standards, however, it still presents information in a new way, so it does require some training for workers to familiarise themselves with it.

One of the concerns when it comes to the automation of tasks through AI-based and robotic systems is the process of deskilling. Automation like this is generally seen as a starting point for one of three skill developments: **deskilling**, **reskilling** or **upskilling.**

While significant parts of the worker's routine are minimised or have become redundant (for example, putting on the safety gear for inspection of the vessel's interior), the knowledge of how to do so is still part of regular safety training. Also, not all vessel inspections are carried out by the robotic solutions, as they are not yet employed at all locations, so these skills still remain relevant. The same can be said about the disassembly and reassembly of the tanks. **The skills and knowledge are still relevant and will remain relevant** for the foreseeable future, as replacing parts due to wear and tear will continuously be needed. Thus, from the perspective of the gas infrastructure operator, the robotic systems do not contribute to deskilling. The introduction of the robots is instead perceived as a form of upskilling. Handling the robotic system does require new skills from the operators, as it is a new technology. This does expand their qualification portfolio and can be described as **upskilling**.

4.3.2 Feedback system and report handling

Workers tasked with the inspection of the gas vessels are highly skilled technical engineers. Their feedback has been collected from the early stages of development onwards to optimise the robotic systems. Feedback continues to be actively encouraged as there are still new features being developed and tested. Based on their working experience with the robotic systems, workers' feedback on the systems has been positive. The customisation options of the robotic crawler (for example, adding ultrasound probes if wall thickness needs to be determined) are highlighted and the overall technology is described as an important step for improved worker safety. So far, there have been no major OSH-related reports, however, any and all concerns can be brought forward and sent to the developers.

4.3.3 Level of trust and control

An adequate level of human trust towards the interacting system promotes appropriate system use,[5,6] while extreme forms of trust can lead to adverse effects. Excessive trust can lead to automation complacency,[7] whereas insufficient trust may lead to neglect of the technology.[6]

So far, the system has received **positive feedback from the operators**, who seem to trust in both the accuracy of information provided by the two robotic systems and the safety features added (for example, the gas detector and rapid shut down).

In addition to trusting the system, a worker's level of control can have significant influence on a number of factors. The operators have full control over the two robots. While the crawler can move autonomously, the

[3] Waldeck, N. E. (2000). *Advanced manufacturing technologies and workforce development*. Garland Press.

[4] Fraser, K., Harris, K., & Luong, L. (2007). Improving the implementation effectiveness of cellular manufacturing: A comprehensive framework for practitioners. *International Journal of Production Research, 45*(24), 5835-5856. https://doi.org/10.1080/00207540601159516

[5] Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors, 39*(2), 230-253. https://doi.org/10.1518/001872097778543886

[6] Hancock, P. A., Kessler, T. T., Kaplan, A. D., Brill, J. C., & Szalma, J. L. (2020). Evolving trust in robots: Specification through sequential and comparative meta-analyses. *Human Factors, 63*(7), 1196-1229. https://doi.org/10.1177/0018720820922080

[7] Parasuraman, R., & Manzey, D. H. (2010). Complacency and bias in human use of automation: An attentional integration. *Human Factors, 52*(3), 381-410. https://doi.org/10.1177/0018720810376055

operator also has the option to switch to manual inspection, should an area need a more detailed inspection. The robotic arm, too, can be operated manually by the inspectors. So far there are no indicators that the operators experience a loss of control while working with the robotic systems.

4.3.4 Company culture and structure

The introduction of the two robotic systems has not led to larger changes in the company culture and structure. The inspection process takes less time on average than before, however, this does not trigger larger structural changes.

4.4 Future developments

The gas infrastructure operator is indeed planning on developing more robotic solutions to implement at their worksites, especially in the area of long-distance inspection and maintenance tasks for pipelines. Considering that part of the infrastructure is offshore and under water, robotic systems hold the promise to make these tasks more efficient and flexible than before. Furthermore, as the dual robotic system proves effective at the plant where it is currently being used, it will be rolled out to more sites as well. And, as mentioned before, there are still new features being developed and tested for the two robotic systems. Speaking more generally, **they are interested in developing and using innovative technology to make work safer and more efficient**.

5 OSH impact

The introduction of advanced robotics or AI-based systems can have a wide impact on OSH. It can pose a number of challenges as well as opportunities unique to each case study. Therefore, it is important to identify possible barriers and drivers to consider them in future projects. These new forms of task automation can even lead to changes in the overall OSH management of a company. Through the interviews, a number of these factors for this specific case study have been identified and discussed.

5.1 Challenges

As advanced robotics and AI-based systems allow highly individualised solutions for a company, they might also present challenges specific to their use. In addition, more universal challenges can emerge, which the company then has to address. The interviews contained a number of OSH challenges the company had to face, both during the implementation phase and in ongoing production.

5.1.1 Cognitive load

While the workplace itself has changed for the operators, their primary task in the context of the tank inspection has not. It still needs a **qualified, trained worker to assess any findings made with the robotic systems**. However, this task is now also supported by the report produced by the robots. This support could possibly **increase the cognitive load of inspectors**, who need to concentrate on the video material for a prolonged time. However, there are currently no reports of operators regarding this effect. The company only acknowledges that this could be a possible effect.

5.1.2 Fear of job loss

The fear of losing one's job can have negative effects on a person's mental health,[8] and commonly arises in the context of automation.[9] The inspectors working for the gas infrastructure operator did experience a fear of job loss in the context of the robots' implementation process. However, intervention by management helped to ease these fears.

5.2 Opportunities

The introduction of the technology to the production site also held numerous OSH benefits and opportunities.

5.2.1 Safety and health

Increasing worker safety was the primary goal of the automation effort. Working inside a pressure vessel can coincide with several workplace hazards. There are safety hazards, as the inspector would have to enter confined spaces. There are also chemical hazards as the pressure tanks were filled with gas as well as ergonomic hazards due to changing light conditions and possibly poor posture. If a worker is to enter a tank, they wear protective gear in the form of a helmet, gloves, breathing masks, a safety suit and security harness. With both of the robotic systems automating the task of physically entering the pressure vessel for

[8] Bünnings, C., Kleibrink, J., & Weßling, J. (2017). Fear of unemployment and its effect on the mental health of spouses. *Health Economics, 26*(1), 104-117. https://doi.org/10.1002/hec.3279

[9] Spencer, D. A. (2018). Fear and hope in an age of mass automation: Debating the future of work. *New Technology, Work and Employment, 33*(1), 1-12. https://doi.org/10.1111/ntwe.12105

inspection, operators **do not have to enter this dangerous work environment** anymore for inspection. Only once a need for repair is identified does a trained worker enter the tank, in the case where the part can be repaired sufficiently from the inside.

While not as impactful as the removal from a hazardous work environment like the inside of the vessels, the workers are now also less often exposed to weather conditions. While the inspection process would not be performed in too harsh conditions anyway (for example, during storm warnings), exposure to rain, wind and UV radiation can still contribute to negative health effects.

5.2.2 Worker qualifications

The primary task, which is inspection of the tanks and vessels, has not changed. The inspection team still needs to be skilled to be able to determine the state of the material and decide what kind of intervention would be right. The team in charge of dissembling and reassembling the vessel also needs to maintain this skill, even if they perform this task less frequently. However, controlling the robotic arm appropriately is important to gain images of the tanks inside at a sufficient quality. Also, planning a path for the crawler, operating it manually and learning to interpret its report are new skills the inspectors needed to acquire. Overall, **the skill portfolio of the inspection workers has expanded because of the robotic systems**.

5.2.3 Physical workload

While the primary task inspectors try to accomplish is a cognitive one — assessing the state of the vessel and determining the need for intervention — this task could not be completed before without significant physical work. Not only were operators working in heavy safety equipment, they also needed to perform strenuous physical activity. Pressure vessels did not always allow for upright posture and can have a curved surface to walk on. To inspect some parts of the vessels in a crouched position was needed as well. So, performing an inspection of a pressure vessel required physical fitness and was strenuous. After the robotic systems were introduced, many of these physical tasks became redundant, therefore reducing the physical workload of the inspection team significantly.

5.2.4 High-risk groups

Working with the robotic system does not create or affect any high-risk group. As described above, working inside the vessel required the inspectors to be physically fit. This made the workplace accessible to workers without disabilities or temporary injuries. If the technology is expanded upon, and the robotic crawler and arm become able to transmit their footage wirelessly across larger distances, **analysis of the video material could be performed by workers who would previously not have met the physical requirements to enter the vessel**.

5.3 Barriers and drivers

Many companies go through the process of integrating an advanced robotics or AI-based system to their workspace for the first time. The present case study encountered a variety of barriers and drivers throughout this process. Identifying these can help this company as well as others avoid barriers and promote drivers for their process automation.

5.3.1 Barriers

The entire development process was considered rather long. Development of the system started in 2013, and in 2016 initial testing could start. In the beginning of 2019, the system was finalised. This was when the system could actually start inspection tasks.

Recent **global developments** have made the collaboration and development of the robotic systems more challenging. The developments around Europe’s gas infrastructure in 2022 have resulted in additional safety measures. These have made collaboration and the exchange of data more difficult and less seamless. Nevertheless, safety as well as security are the highest priorities at the moment.

5.3.2 Drivers

Collaborating with several experts on the project was seen as a significant success factor. Often, it is impossible to have all the necessary expertise within your own company. So, the success of creating a customised complex robotic solution often depends on working with highly skilled collaborators. Together with these partners, the technical engineer and the gas infrastructure operator could customise and create these robotic solutions.

The collaboration has proven to be very effective overall. By now the team has lessened the time needed for successful implementation at a new worksite down to around a year. In this time frame, the project has also **moved its status from RND** (Results Not Demonstrated) to **Innovation.** This was possible because key end users already know how the crawler and robotic arm work, and they get involved at the start of the implementation phase. From there on, direct communications is the main driver to get new systems completed and on the market.

Another factor that, according to the technical engineers using the system, is a driver for long-term success with this technology is that the systems were designed to be complementary to one another. While the snake system enables the engineers to gain a fast overview of the state of the vessel, the robotic crawler allows highly detailed inspection (which is more time consuming). Being able to use these systems as their strengths are needed contributes to their ease of use. Furthermore, the robotic crawler can be customised even further by adding on machinery, for example, an ultrasound probe, to perform even more in-depth inspections. This flexibility is described as very positive.

From a developer's point of view, having the possibility to **do early on-site prototype testing, under real working conditions, also contributed to the success of the project**. Having the developers onsite, to understand the actual surrounding and conditions in which the final systems would operate, helped them to develop better, more resilient solutions.

From a management perspective, it also was an advantage to only **collaborate with EU Member States**. This provided a common regulatory basis on which everyone agreed and adhered to. This can be more challenging, when collaborating with countries that operate under different laws.

5.4 OSH management

New technology can lead to a change in work procedure. This includes expectations placed on the technology and subsequent OSH management.

5.4.1 Expectations for OSH

The expectations for OSH are largely reflected in the motivators and goals, as improving OSH was a central concern for the company when creating these systems. While the technology is not yet available at all sites, **the experience so far confirms that the expectation of a safer, less strenuous work environment** has been achieved.

5.4.2 Emerging OSH risks and monitoring

Safety inspections and continuous monitoring of risks is already a vital part of operation for the gas infrastructure operator. They are aware of their diverse and challenging work environments and take ample precautions to make them as safe as possible. This is reflected in the extensive safety measures and protective gear an operator had to put on before manually inspecting the gas tanks. So, as the robotic systems were introduced to the workplace, they too underwent risk assessment and are now included in further workplace inspection processes. A **new OSH checklist was created**, which the inspectors use to monitor for any emerging OSH risks. This also includes frequent inspection of all robotic systems for any malfunctions and especially the safety features, like the added gas detector. Both robotic systems also create manual reports on how many hours they have been in active use, and if parts of them need replacement due to wear. Furthermore, they are encouraged to give any feedback or observations on this issue, as the improvement of OSH is one of the main objectives behind this automation.

5.4.3 Communication strategies

Changes to the robotic systems are communicated as needed to the relevant stakeholder. Depending on the extent of the change, the chain of communication varies. When minor software updates (for example, dashboard updates) are released, the operator is informed that there is an update available. When major modifications are made, everyone is involved, including end users and developers. Prior to making any major changes, potential negative consequences are discussed. Once the changes are agreed on, they are forwarded to the developers, who then begin implementation.

In addition, there is an **annual meet up of the project team**. Here, all stakeholders and developers get together and everyone has the opportunity to present their priorities in the project. Through discussion and compromise, the next steps in the project's development are decided upon.

5.4.4 Organisational and social impact

These technologies have had organisational impact; or speaking more generally, will have, once they become more widespread. Given that an inspection used to take up to three days, having a technology that reduces this time significantly allows the organisation to plan their workflow differently. Vessels can be inspected more frequently, and workers experience less down time in between inspections.

5.4.5 Integration of OSH management

With the development and implementation of the two new robotic systems, there were also some changes made to the standard OSH procedures for the inspection task. Firstly, a risk assessment is performed at every asset prior to employing the robots. Secondly, new safety checklists were developed for the robotic use specifically, which are now part of the routine. These checklists still need to be generalised in the future to allow their use on a more global scale.

5.4.6 Need for action

Currently, there is a need among the collaborators on this project to create a system that operates more seamlessly than before. Harmonising topics like data transfer and communications, without sacrificing cybersecurity and data privacy, is a difficult undertaking.

Furthermore, the regulations to implement advanced robotic systems at workplaces in some European countries are making the implementation more difficult. They are described as being ‘conservative’, and not reflective of today’s technological capabilities. This does not only apply to robotic systems but also for other advanced technologies like drones. Regulations relevant to the employment of these two specific robotic systems are described as being older than the technology. The interviewees formulated a wish for regulators to put increased effort into updating robot-related regulations to reflect the technological capabilities. One way to achieve this is to have a more active collaboration between legislators and the industry.

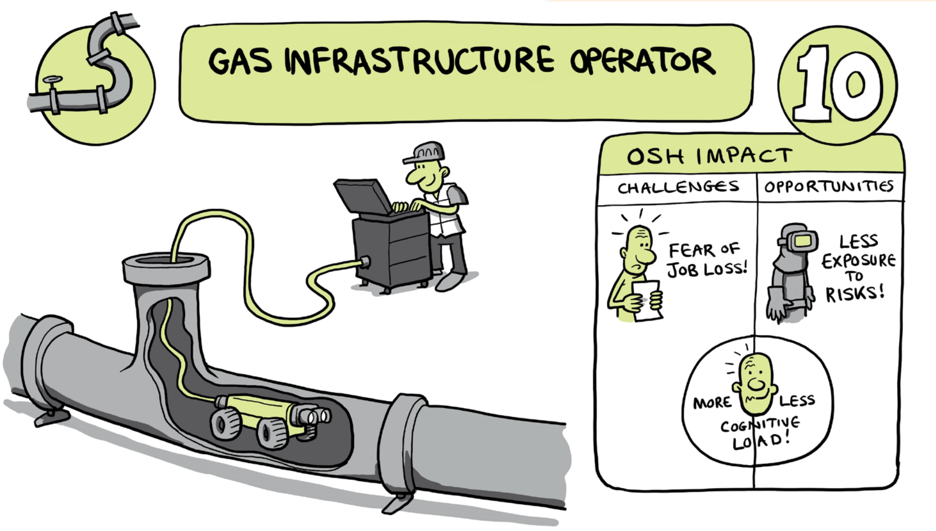
5.4.7 Cybersecurity

With technology becoming increasingly interconnected and data being a resource needed by some AI-based systems to improve their functionality, the topic of cybersecurity becomes prevalent in companies employing these technologies. The way that cybersecurity is handled at a company level is a key factor in securing the data when it comes to AI-based systems. Some systems require additional safety measures, depending on their use. The camera system on the robots is only used inside the vessels. Operators are not actively recorded and no person-related data are stored. Hence, there are no major concerns of data privacy being at risk due to the robots.

The robotic systems themselves are stand-alone systems, which are not connected to any larger network, making them an **unlikely target for a cyberattack**. Being a gas infrastructure provider, they already have extensive measures in place to ensure security from external forces. However, given global developments concerning the gas infrastructure in Europe, in light of the destruction of major gas pipelines, additional safety measures are taken and given high priority.

A cartoon-style representation of the system, including some of the challenges and opportunities for OSH is presented in Figure 3.

Figure 3. Advanced robotic systems for inspection and maintenance, posing challenges and opportunities for OSH



6 Key takeaways

In this case study, the gas infrastructure provider **worked together** with robotics development teams and other stakeholders to create two robotic systems capable of assisting in a physically dangerous and exhausting task. Interestingly, their development process has led them to create **two specialised systems** rather than one robotic system performing all facets of the task. While the robotic arm can provide a quicker overview of the worksite, the wheel-based robotic crawler operates more slowly but can provide more detail. This highlights that stepping away from the idea of one system fits all and towards specialised solutions can be a major success factor when it comes to robotic automation. What one commonly perceives as a single task performed by one person often is a number of complex subtasks, which require an immense spectrum of capabilities. Robotic systems imitating the abilities of humans can drive innovation, however, trying to create a single system that is capable of all needed skills can be more of a barrier than a driver. Splitting functionalities between several technologies allows robotic developers to create systems that excel at one or two tasks without having to compromise functions to make space for additional abilities. When looking for opportunities to automate tasks, developers should not only consider what type of robotic system we need, but also how many.

Another key takeaway can be found in the custom robotic solution that this case study presents. The wheel-based robot is equipped with the unique feature of magnetised wheels. This way, it can drive around the entire pressure vessel. When constructing or choosing an advanced robotic system to automate a task, one should take into consideration **the unique environment** it will be employed in and how its **construction could be altered** to better perform its task more efficiently. Stepping outside the box and including the environment's opportunities for innovation can help in creating a better system.

The final takeaway concerns the topic of collaboration and communication. While it is true that communicating with a large team that includes many stakeholders comes with its own set of challenges, this case study highlights that the benefits far outweigh them. Gathering expertise from different specialists helps drive innovation. Regarding this collaboration, the advantages of working with European collaborators is also highlighted. The shared legal and value system makes working together easier and more efficient.

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