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Advancements in Remote Maintenance: Designing for inclusive human-machine collaboration in autonomous offshore hydrogen production

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Advancements in Remote Maintenance: Designing for inclusive human-machine collaboration in autonomous offshore hydrogen production

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A design philosophy for augmented human-machine interaction

The complexity of deploying humans to remote, weather-exposed offshore locations with hazardous working environments, such as offshore energy production, implies increased occupational risks from transportation, accidents, or exposure to dangerous work situations, high operational costs and less sustainable modes of operation. Considering such factors, the offshore energy sector is in transformation, gradually shifting safety-critical maritime workplaces to shore-based remote operation centres supported by digitalisation. In this paper, we examine a large-scale project combining offshore wind energy and hydrogen production to develop a systemic perspective. Another important driver for change is the net-zero transition, where cost and sustainability may seek benefit from remote operations, but our broader sociotechnical system analysis has revealed entanglements related to occupational risks, complexities related to elements such as human-centred design, inclusion, ethics and qualification requirements for the future on-shore workforce. In this context, we argue the need for novel approaches to human-centred operations focused on remote collaboration and related interactions among humans, robots and 'intelligent automation' (e.g., cyber-physical systems). Our work applies a systems oriented design approach and explores how an overarching human-centred and system-oriented approach, combined with visual, perceptual and design

research, is especially valuable in the early phases of innovation, helping to address systemic challenges and to establish a design philosophy for the future of inspection, maintenance, and repair operations in offshore hydrogen production. That can be used to outline inventions, further design research and help define experiments that potentially could help the industry navigate towards an inclusive and human-centred integration of technology in future inspection, maintenance, and repair operations.

KEYWORDS: net zero, green hydrogen, offshore wind, remote operations, autonomy, industry 5.0, human-machine collaboration, artificial intelligence, human-centric cyber-physical systems, inspection, maintenance & repair, system-oriented design, human-centred design, visual perception, extended reality, robot telepresence, sociotechnical systems, remote maintenance, offshore hydrogen production

RSD TOPIC(S): Sociotechnical Systems, Cases & Practice, Mapping & Modelling

Introduction

The global energy sector is transforming towards the decarbonisation of energy production by scaling renewable energy sources, such as the future novel combination of offshore wind and hydrogen (International Energy Agency, 2022). In response, we applied a new offshore hydrogen substation named Hydepoint as our case study, focusing particularly on challenges related to maintenance in its future operation (Hydepoint, 2023). Looking at the wider system (Figure 9), we see that scaling this combination in the future requires the establishment of a successful business (IEA, 2022), and digitalisation plays a key role in lowering costs (Klonari et al., 2021). Hence, scheduled for introduction at scale beginning around 2030, future offshore hydrogen factories may operate as unmanned autonomous and remotely operated assets (Hydepoint, 2023). However, such highly automated remote operations may still require some level of human supervision (Bainbridge,1983) and a certain level of human-supported inspection, maintenance, and repair (IMR).

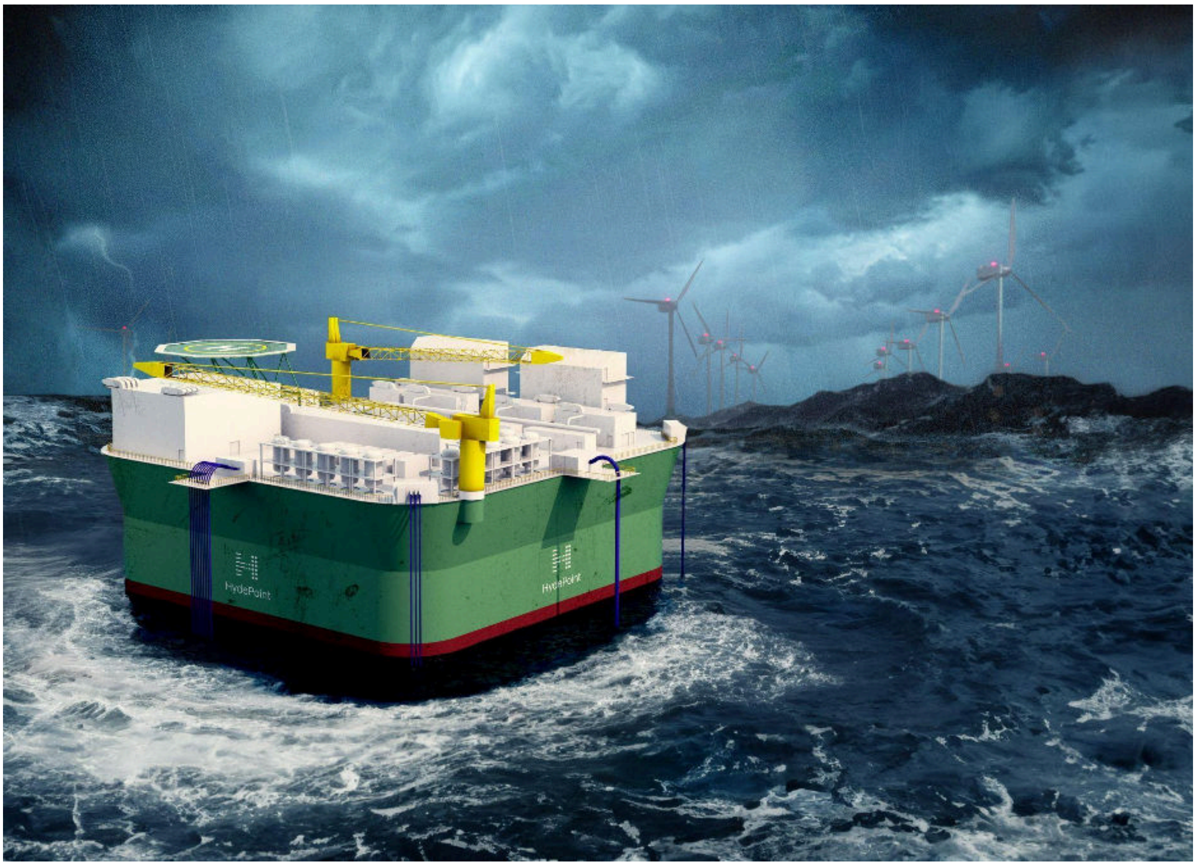

Figure 1: Concept illustration of the Hydepoint substation for future operations (Hydepoint, 2023).

To enable operational efficiency, lower emissions and cost reductions, advanced digitalisation and physical reality must be combined using intelligent automation systems, called cyber-physical systems (CPS) (Chen et al., 2014; Inderwildi et al., 2020). Furthermore, to reduce costs, risks and emissions, most onshore remote operators may perform their work without physically attending to offshore installations, potentially supported by autonomous robotics (Bengel et al., 2009), digital twins (DTs) and extended reality (XR). Hence, we argue that in parallel to engineering a future offshore hydrogen substation, it is crucial to establish an understanding of how humans and such future systems can safely and efficiently work together.

In our study, we learn from the offshore energy industry that humans should not be replaced by automation, but it can be used to make human work safer and more efficient (Windpower Monthly, 2021) and less emissive. In other words, technology can be used to augment humans and their work and to support business goals and the net-zero transition. Yet, integrating human oversight, competency, and collaboration into such remote, semi-autonomous and autonomous operations is complex, especially in the context of future remote IMR, as humans traditionally handle such work. Further, the topside equipment on the hydrogen substation (at least for now) is designed primarily for human handling, a temporal complexity considering that human-machine collaboration in remote IMR will not achieve a 'finished state' until 2030 but will evolve iteratively over time before its launch and over decades of operation. Thus, integrating human-machine collaboration into future operations, such as for Hydepoint, necessitates entirely original approaches to human-centred operations, as well as a sociotechnical systems (STS) perspective. This article is an early attempt at enabling a broader understanding of the need to study human-machine collaboration in relation to the future remote IMR context. By applying a system-oriented design (SOD) process, we seek to understand better the complexities involved in and to develop an early yet comprehensive understanding, identify key opportunities and challenges and outline a pathway towards establishing an inclusive human-centric design philosophy for IMR operations. Relating back to the creation of successful, safe and sustainable business models, which may be paramount to support the net-zero transition (IEA,2022), we ask how we might organise the most important challenges in applying human-machine collaboration in this type and scale of industry energy project.

This paper serves as a starting point in exploring the evolving nature of IMR activities within the offshore energy sector. As the sector becomes increasingly automated and remote, further study of these areas will be essential for a successful transition to the future of offshore energy operations. Answers to these questions will shape not only the future of IMR but also the future of the industry and potentially the future of human habitability and prosperity.

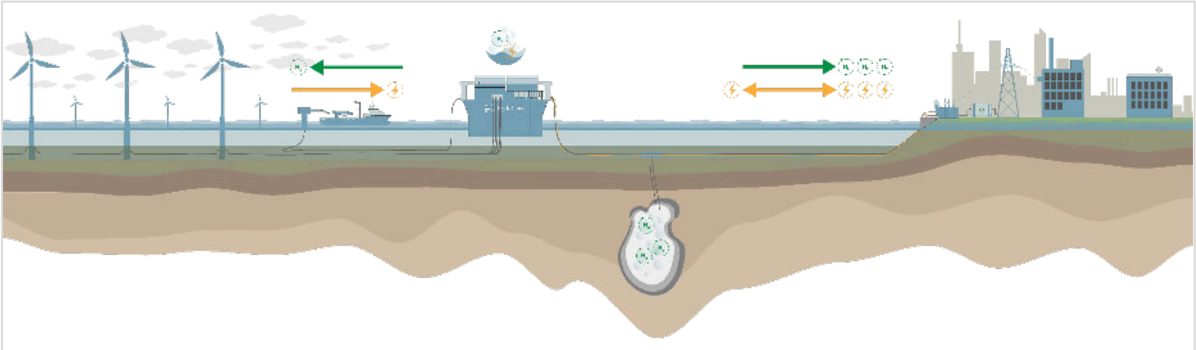

Figure 2: Concept model of the Hydepoint operational landscape and energy flow, where green arrows illustrate hydrogen and orange arrows electricity (Strange, 2023).

Hydepoint and offshore hydrogen in the net-zero landscape

Offshore wind energy is an established source of renewable energy that continues to undergo scaling to meet the increasing renewable energy demands sparked by the net-zero transition (Kühn et al., 2022). In addition, green hydrogen produced with renewable energy is expected to increase alongside other renewable energy sources (IEA, 2021), including offshore wind. Thus, introducing hydrogen-producing substations to offshore wind operations promotes the establishment of wind-rich locations to harness in full the potential of such a combination (Calado & Castro, 2021). Hydrogen production substations that electrolyse seawater can act as energy 'buffers' to stabilise offshore energy production by converting and reconverting hydrogen into electricity, reducing the necessity for an extensive onshore power grid expansion, and they can utilise the full energy potential of offshore wind farms. It can also allow the conversion of surplus onshore energy into hydrogen and the later reconversion into electricity when needed, which may help balance and 'buffer' energy production (see illustration in Figure 2; Calado & Castro, 2021).

It will take time to engineer, test, scale up and devise new concepts before hydrogen-producing substations are operational, seeing first gas around 2030, followed by further scaling into the future. To succeed, a profitable business appears to be a key element of future offshore wind and hydrogen scaling (IEA, 2022), and a significant focus on cost reductions now drives incentives for development.

Remote and autonomous operations

Our study indicates that creating a sustainability business for offshore hydrogen is dependent on three core elements: human safety, capital expenses (CAPEX), operational expenses (OPEX) (Furru, 2019) and sustainability. The industry aims to address these through applying unmanned, autonomous and remote operations.

There is currently significant CAPEX and OPEX in permanently manned operations (Niven & McLeod, 2009) and manual IMR related to the installation of accommodation units, advanced detection and safety systems, emergency systems, the related enforcement of safety procedures and staff training and routine inspections (Furru, 2019). For Hydepoint, there are significant safety issues related to the production of hydrogen, given its properties in relation to human non-detectability and the risks of fire, explosion, asphyxiation from oxygen displacement and freeze injuries from exposure to liquefied gas (Martek Marine, 2021; Vestrheim, 2022). Furthermore, transport by helicopter or crew transfer vessel to and from weather-exposed offshore introduces additional risks, expenses and emissions and is difficult during poor weather conditions (Baker Hughes Company, 2023).

It is currently increasingly common to support offshore operations when necessary by using offshore service vessels that can transport technicians who are supervised by a remote operation centre (ROC) (Dudgeon, n.d.). In the future, to address cost, safety and sustainability challenges, the offshore renewable energy sector will likely carry out and oversee most safety-critical operations from shore-based ROCs. A relevant upcoming practice in the offshore wind sector will be to have one ROC supervise multiple offshore wind farms (Dudgeon, n.d.; Windpower Monthly, 2021), reducing organisational size and consolidating it around remote operators, technicians, experts and related support functions (Johnsen et al., 2005), as illustrated in Figure 3.

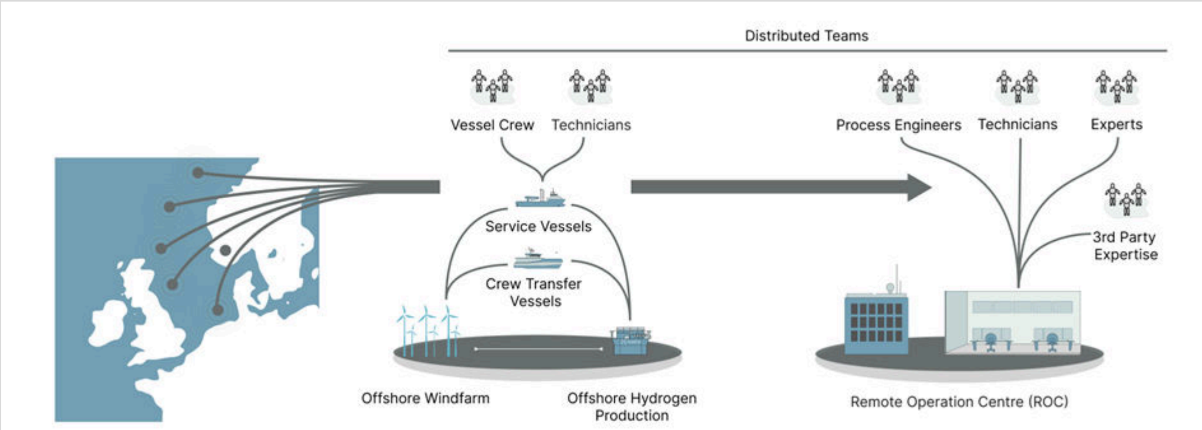

Figure 3: Illustration of a remote and autonomous multi-field wind farm and hydrogen operations supervised by the remote operating centre (ROC) (Strange, 2023).

However, we assume that over the course of the next three decades, the operational context may shift when current procedures and systems are challenged to reform. In this context, industrial artificial intelligence (AI) capabilities may evolve, introducing new developments to automation systems, where future autonomous production units may become more 'intelligent' (Hepsø & Parmiggian, 2022) with self-learning (machine learning) and self-optimisation (big data and historic data analytics) capabilities (Mohammed et al., 2022; Moness & Moustafa; Werkhoven et al., 2018), also referred to as cyber-physical systems (CPSs; Chen et al., 2014). An autonomous CPS could blend digital and physical interaction through action-reaction feedback loops (Chen et al., 2014). Hydepoint could, for instance, self-optimise to balance the production of electricity and hydrogen based on the weather conditions or onshore consumption or energy needs. Or perhaps, learn from historical data to optimise operations for seasonal demands, weather or trade.

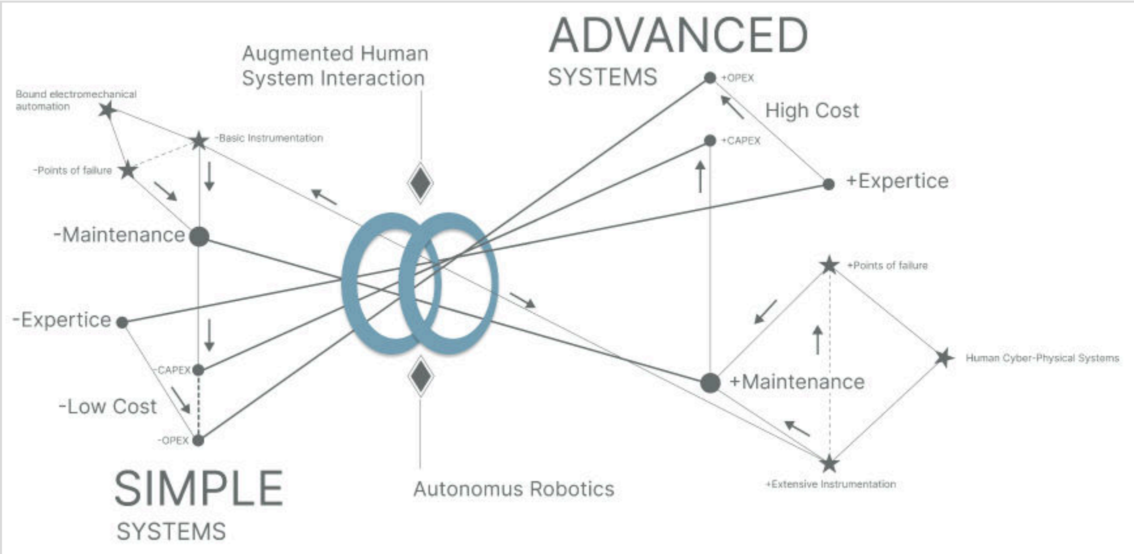

Figure 4 Illustration of paradoxes inspired by Jones and Van Ael (2022) in high-level versus low-level automation and instrumentation, with an overview of their interrelations and two elements that honour both sides (Strange, 2023).

Advanced systems with increased levels of automation may have multiple sensor networks installed, which may increase both costs and the demand for maintenance. In contrast, simpler systems require lower competency and more human involvement at a lesser cost and with lesser maintenance. Yet, the 'bound' nature of simple systems makes them best suited for localised offshore operations on the asset, as such systems lack the connectivity and technology to integrate with shore-based operations (Hepsø & Parmiggian, 2022). This creates a paradox (Figure 4) in the context of IMR in unmanned, autonomous and remote operations, where simpler solutions may be more resilient, require less expertise and cost less, but they may also require human presence offshore and transportation to and from the weather-exposed remote locations, reducing their functionality, safety and sustainability. Advanced systems may reduce OPEX, but with more sensors, they might not represent the opposite of simpler systems in the context of unmanned operations and related IMR. Rather than selecting one or the other extreme, it seems honouring both sides could improve resilience and system robustness (Jones & Van Ael, 2022).

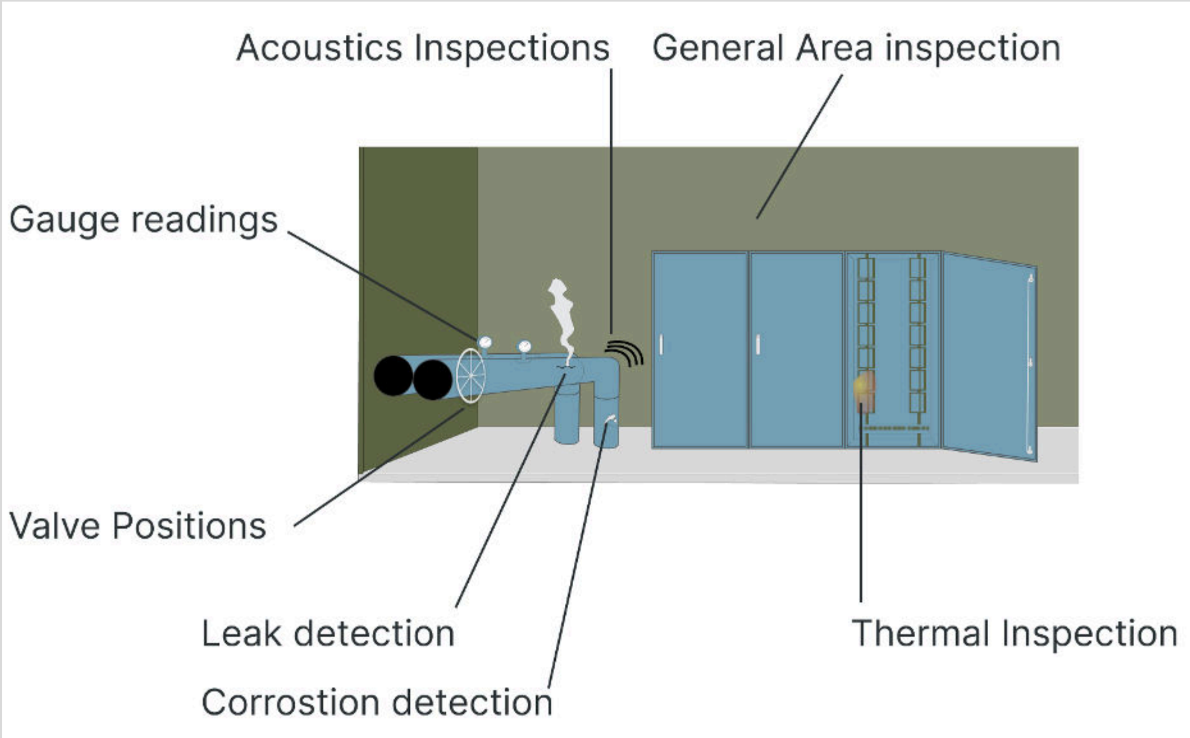

Figure 5: Illustration of typical topside inspection, maintenance and repair (IMR) activities (Strange, 2023).

Inspection, maintenance, and repair in 2030 and beyond

“Hydepoint will contribute to reduced costs in the global large-scale build-up of offshore wind that is planned over the next 20 to 30 years” (Arendalsfossekompani, 2022), where unmanned operations are considered important to reduce costs (Hydepoint, 2023). In this paper, we seek to illuminate the importance of considering IMR and its role in the emergence of unmanned, autonomous, and remotely operated offshore energy operations.

The IMR of offshore energy operations is essential to operational integrity, compliance and safety, and, as mentioned earlier, it represents a significant operational cost. (G. L Garrad Hassan, 2013). There are three primary areas of IMR: submerged (underwater), the splash zone (areas near the water line) and the topside (installation above the water line), the latter of which our study has identified as particularly challenging in a future unmanned, autonomous and remotely operated context.

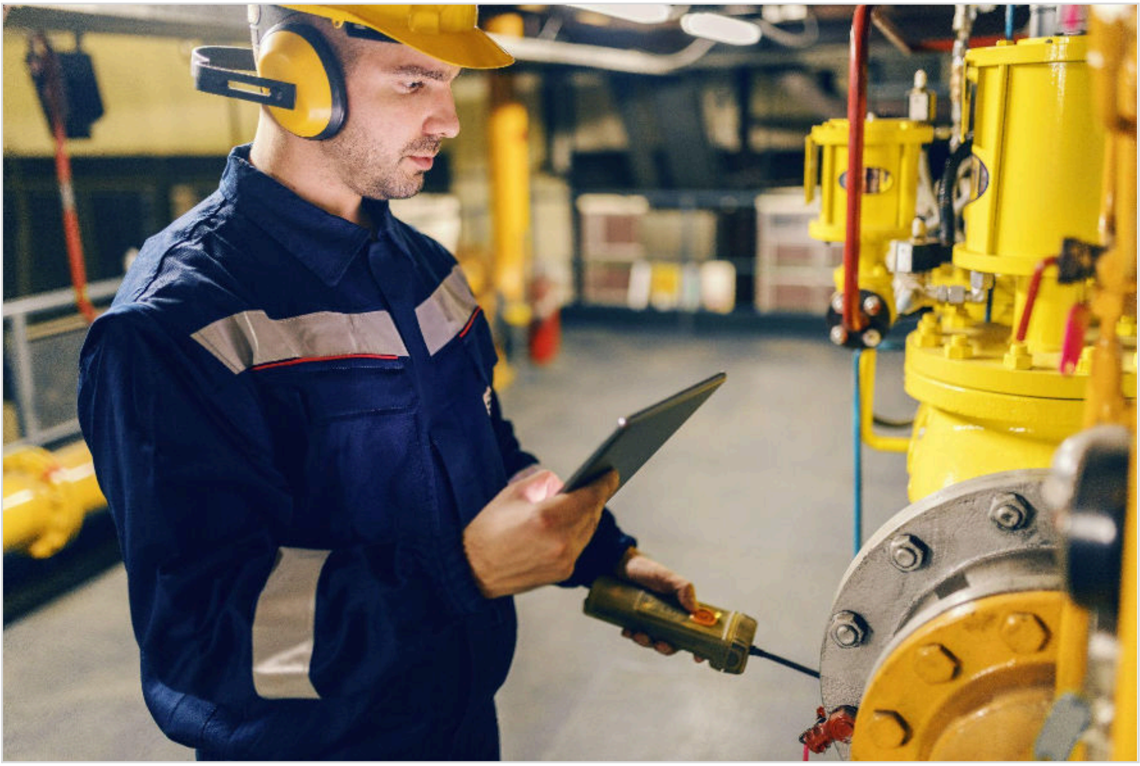

Figure 6: Illustration of manual topside inspection of process pipes. (Dusanpetkovic, n.d.).

Topside IMR represents a mix of scheduled routine tasks and unscheduled tasks related to predicted, observed and unforeseen events, as illustrated in Figure 5. However, our study identifies IMR as a distinct challenge, partly because these environments, its equipment and its accessways continue to be designed for humans and manual human–physical interventions (Figure 6) and partly because there will be no humans onboard for much of the operational time. Further, a robust design, redundancies, safe degradation and similar strategies combined with sensors and camera systems may alleviate some manual human work (Hepsø & Parmiggian, 2022). However, if offshore wind and hydrogen venture into more exposed areas, there will be limitations in terms of weather widows (Hadjoudj & Pandit, 2023), which could imply that sometimes non-human entities or systems must tackle daily IMR aspects.

How will advancements in technology change the landscape of such IMR operations, and what are the implications for the future human workforce and its tasks (Figure 6) with the shift from human- to remotely managed operations? In addition, what will the return on investment be for implementing innovative technologies and ways of operating, and how will it affect the overall OPEX of offshore wind and hydrogen industries? Further, how will the industry balance the costs of innovation and the potential savings from the increased efficiency and reduced human presence? Again, we refer to our main question: How can we organise the most important challenges in applying human-machine collaboration based on this type and scale of offshore renewable energy project?

Establishing a systems perspective

Why apply a systems perspective?

Our study for this paper served as a starting point in exploring the future of IMR activities within the offshore energy sector from 2030 and beyond. As the sector is evolving towards automation and remote operations, each multifaceted entanglement, from human resources and competencies to technology, operational processes and safety protocols, interacts with and influences one another. Accurate predictions of the future ten or more years ahead are complex, and although there might be relevant methods for speculation, we, inspired by Russel L.Ackoff, choose to begin with current assumptions.

> The future is better dealt with using assumptions than forecasts.
> (Ackoff et al., 2007).

Because such operations are assumed to become increasingly automated and remote, further study of these areas will be essential for a successful transition to the future of offshore energy operations. For instance, introducing innovative technologies might affect required competencies and skill sets, which in turn could impact recruitment, training and the overall workforce strategy. Similarly, changes to operational procedures could have implications for the design and maintenance of equipment and the health and safety of the workforce. By adopting a systems perspective, we may begin to explore ripple effects, outline interventions and make better-informed decisions. Yet, how can we best consider the broader implications of changes rather than viewing them in isolation? Applying a systems perspective is about understanding not only the individual elements but also how these elements work with each other, the interrelations they establish and how they influence each other (Sevaldson, 2021).

Systems-oriented design for rapid learning of sociotechnical super-complexity

> The key to systems thinking is to sweep sufficient information, from various different viewpoints, to paint a rich and complex picture, but without compromising the meaning of analysis by over-inclusion, thereby paralysing action (Ulrich, as cited in Midgley, 2000).

Addressing the sociotechnical complexity introduced in our case necessitates a participatory process of the interactive externalisation and internalisation of knowledge from experts, literature and other viewpoints to establish the system we are 'designing within' and to produce and share relevant knowledge of value (Sevaldson, 2021). Again, we ask, "How can we organise the most important challenges in applying human-machine collaboration in this type and scale of industry energy project?" We face a complex system and a scenario evolving with time, where significant information is both available and lacking. Simultaneously, we must engage with experts having considerable experience and knowledge, whilst also gathering data from other sources, such as research literature, the internet, technology and other stakeholders. This may, at times, entail what Sevaldson referred to as the "catch-22 of learning about the problem:"

> You cannot gather relevant information about the issue at hand before you know about it. However, you cannot know the issue before you have gathered relevant information. (Sevaldson, 2022)

As the process of learning and establishing a systems perspective becomes difficult to structure linearly, dealing with one thing at a time may become 'overwhelming for the designer that must investigate and enrich their understanding' (Sevaldson, 2022). Working with complex systems, as in our case, we must facilitate what SOD refers to as a very rapid learning process (VRLP) related to the system and the complexities they are facing. The process should be action-oriented (Midgley, 2000; Sevaldson, 2013), and SOD designers must themselves be part of the system they are designing.

Figure 7: Gigamapping workshop 2 on the Hydepoint concept, tackling the sociotechnical landscape (Strange, 2023).

In our case study for this paper, we used Gigamapping and zoom, innovation, problem or potential (ZIP) analysis in workshops (Figure 5) to externalise existing and tacit knowledge (Sevaldson, 2022) and to facilitate visual 'jumping conversations' to shift among various perspectives, topics, layers, scales and system boundaries (Wettre et al., 2022). It can also be applied to learning, literature and other sources of information, such as, in our case, video conversations with experts in offshore IMR, autonomous systems engineering and human interface design for autonomous robots.

Systemic design, in which SOD resides (Sevaldson,2021), is "concerned with higher order systems that entail multiple subsystems." Jones, (2014,p.2) approached from 'multiple perspectives' with a focus on understanding 'fields of relations and patterns of interactions' (Sevaldson, 2021, 2013). To synthesise and visualise the preliminary findings of the VRLP, we have designed a preliminary high-level representation of the operational landscape and STS.

Sociotechnical system perspective

> Every wicked problem is essentially unique.
> (Rittel & Webber,1973)

Arguably, so are complex systems; hence, we can observe that no one single theory or methodology will fit the SOD process generically, as it must be pluralistic and 'undogmatic,' chosen from more than one theory, method and methodology (Sevaldson, 2013; Midgley, 2000).

Developing an offshore hydrogen operation may represent a system innovation, integrating technology and societal utilisation in a 'co-evolutionary process' (Geels, 2005). Further, technology and social systems are interlinked through temporal interaction patterns (Latour, 1990), forming networks of entities, individuals or groups that actively influence each other in sociotechnical transition processes (Latour, 1990; Geels, 2005), as illustrated in Figure 8.

We apply multi-actor network (MAN) theory (Geels, 2004, 2005), based on actor-network theory (Latour, 1990), to compose a systemic VRLP internal STS perspective, creating an actor-network where the 'actors' are entities, individuals or groups that actively participate in or influence the STS transition process. Actors might include government agencies, various maritime and offshore industry actors, technology suppliers, user groups and various other similar actors. In these networks, sociotechnical interaction occurs along 'chains', where each actor plays a unique role and supports both reproducing systems and shaping technological and societal systemic changes (Latour, 1991; Geels, 2005).

To visualise a systems representation of our findings in this case study, we synthesise a second Gigamap (Figure 7) showing the identified actors and their relations to the multi-level perspective (MLP), a theoretical framework for analysing long-term technological transitions and systems innovations. According to MLP theory, changes in STSs occur at three analytical levels: the landscape, i.e. the wider sociotechnical context; the sociotechnical regime, i.e. the core of established practices and regulations; and the niche, i.e. 'the locus for radical innovations'. These three levels interact and 'co-evolve', driving the transition from 'one sociotechnical system to another' (Geels, 2004,2005).

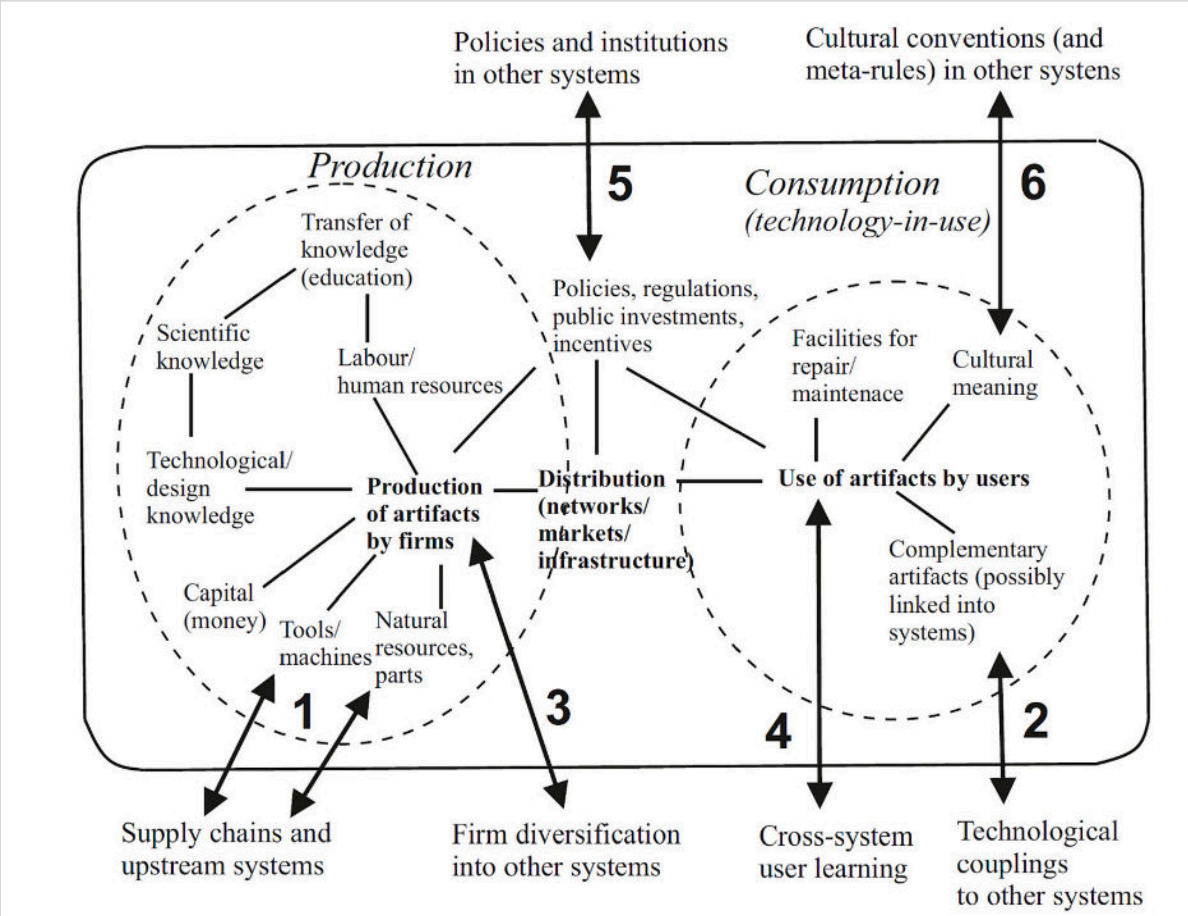

Figure 8: Illustration of elements in a sociotechnical system and relations it might have to other systems (Andersen & Geels, 2023). Licence: Attribution 4.0 International (CC BY 4.0).

Gigamapping

During the most extensive SOD workshop on Hydepoint, a ZIP analysis and related discussion identified IMR as a topic that would benefit from a deeper exploration due to the considerable level of ambiguity in future operations. As such, the goal herein is to 'unpack' this complexity. In Figure 9, we see how this 'unravels' from the exogenous landscape pressure of climate change and the net-zero transition to the existing renewable offshore wind regime, which is changing following the introduction of offshore hydrogen and its future vision for remote and autonomous operations.

In addition, when niche technologies rise to the level of the new regime, the window of opportunity created by the regime change and unfulfilled needs related to safety, costs, efficiency, sustainability and other categories is closed. Thus, how can we explore the future of work concerning IMR operations and its relation to such niche technologies?

Exploring the future through technology

The vision of our case study is unmanned operations supported by autonomous systems and onshore remote operations. This is not new to the offshore energy sector (Hepsø & Parmiggiani, 2022); yet prolonged unmanned operations in the context of IMR on a hydrogen production substation are novel.

Technology is a key element shaping systems innovations and STS transitions (Geels, 2005) and it's important to analyse the role of technology when studying complexity and systems changes. This is a relevant step in our case, given that the 'first gas' starts in 2030, with IMR developing within the year. In this context, our mapping, discussions and literature reading have enabled a revision of three technological niche trajectories that may benefit future IMR, and that can serve as a starting point for 'unpacking' the future of work and its social impact.

Industrial autonomous robots are incrementally being deployed in the field. These can be equipped with a sophisticated suite of sensors, enabling them to self-navigate, conduct autonomous routine inspections, and even operate under offshore conditions (Figure 10 Left). Current iterations may necessitate the presence of an onsite human operator to establish inspection routes, define tasks and remove obstructions (ANYbotics, 2023). Progress in the field of autonomous robotics is leading towards physical manipulation capabilities (Boston Dynamics, 2023), which might be required for certain IMR tasks, unsupervised autonomous navigation and auto-planning missions.

Yet, unless there is a significant shift in the approach to designing process equipment and substations, both elements will continue to be designed by humans for humans, even if the plan is to operate them unmanned. This also implies the positioning of equipment within a human's reach, necessitating human-like dexterity for equipment manipulation, repair, or replacement.

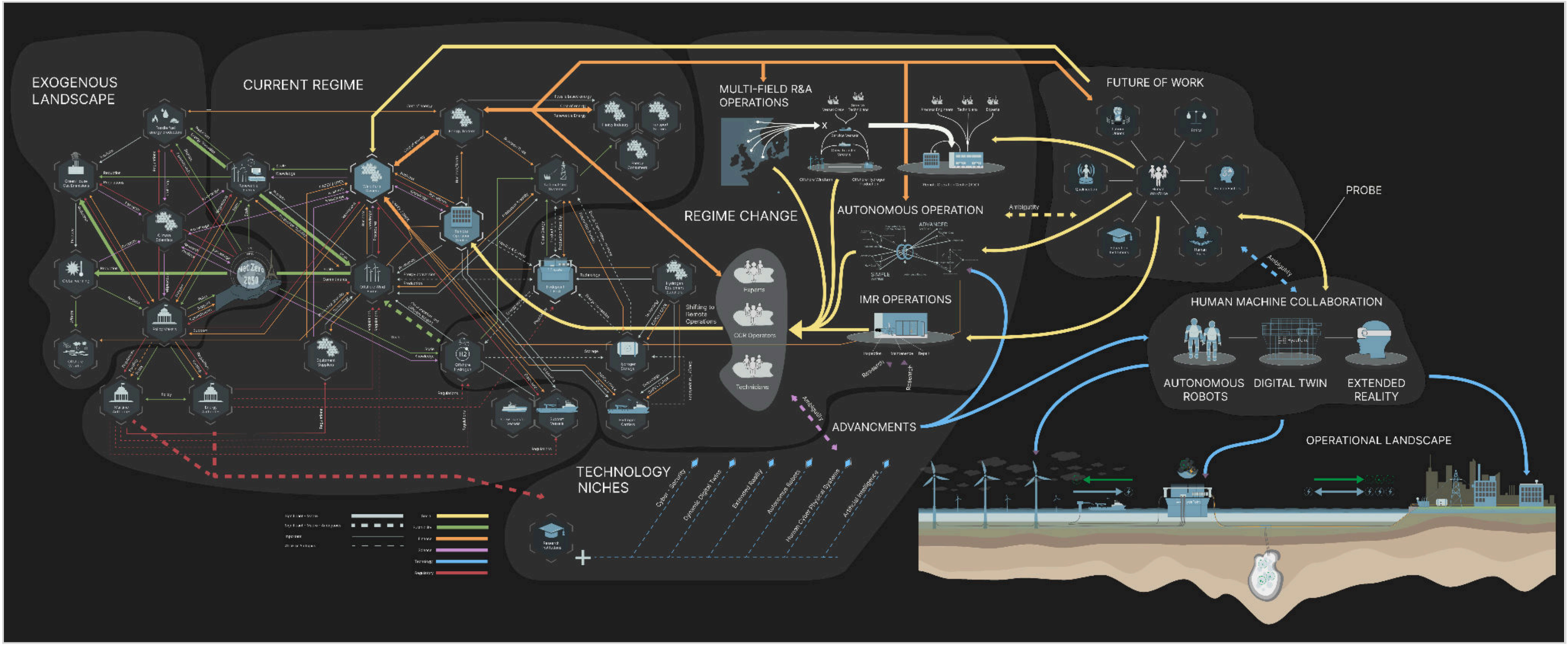

Figure 9: Illustration of the first version of a synthesised very rapid learning process (VRLP) Gigamap based on the workshops, literature and decisions involved in the study (Strange, 2023).

Figure 10: Left: ANYmal industrial autonomous inspection robot conducting a visual inspection of process equipment (AnyBotics, 2023). Right: Picture of an early version of 1X's humanoid robot, showing some dexterous capabilities (Strange, 2023).

While mobile robots inspired by animal movements have shown promise, they may lack the full range of human motion and dexterity. Thus, advancements are being made towards more humanoid robots (Figure 10, right) with enhanced dexterity capabilities (Sanctuary AI, 2023), which, if industrialised offshore, could serve as a flexible vehicle for remote IMR capabilities. A hybrid approach combining animal-inspired and humanoid designs might be useful, especially considering the former's ability to carry sensor payloads (Figure 10, left). However, in our case, questions must extend beyond the technical value of mobile sensor platforms to consider how humans would interact with next-generation autonomous robots in an offshore hydrogen remote IMR context.

Human-robot interaction (HRI) and collaboration across communication channels, a physical context of which operators are not physically a part, can lead to confusion, mistakes, and miscommunication. In addition, autonomous or semi-autonomous systems make decisions that can be difficult for humans to understand, thus hampering collaboration between humans and machines. Video, audio, and data streams are useful, but they do not support the full sensorial experience of being on location, thus reducing humans' ability to understand the spatial situation in situ when relying on video, audio, and data (de Barros & Linderman, 2009).

Addressing these aspects collectively in relation to remote communication, processes concealed beyond human communication references and the inability to engage all senses and motor skills fully when examining a physical situation introduces a layer of complexity that may require careful consideration of system interaction design and HRI in this context. (de Barros & Linderman, 2009).

A crucial aspect in this context relates to whether operators, experts, technicians, or other relevant onshore personnel should have the capacity to control the robot and intervene physically with the process equipment remotely. Given the uncertainty of the future capabilities of autonomous robotics and AI in general, it is likely that robots in unmanned operations would need to be remotely operated using telepresence, where the robots represent human avatars that perform IMR tasks.

In such a case, the degree of experienced telepresence relates to whether the operator 'feels present in the mediated environment, rather than in the immediate physical environment' (Steuer, 1992). Telepresence can be achieved through XR technologies, whereas optical see-through augmented reality (AR) glasses combine digital information with the physical environment in real-time (Milgram et al., 1995; Baraas et al., 2021). The human operator's sense of presence will, in this case, be multi-dimensional and distributed (Benyon, 2012). In our case, for example, the ROC as a physical environment will require the operator to shift attention between different contexts at different distances, whereas the digital information presented by the AR system and different contexts in the physical environment may contain additional sources of digital information (i.e. portable and fixed two-dimensional installation displays; Gallardo-Calles et al., 2013).

An operator will feel a higher degree of telepresence in virtual reality (VR), as this is a digital-only environment (even with external cameras that allow video pass-through to blend the immediate physical environment with the virtual context). However:

> Factors influencing whether a particular mediated situation will induce a sense of telepresence include the following: the combination of sensory stimuli employed in the environment, the ways in which participants are able to interact with the environment, and the characteristics of the individual experiencing the environment. Thus, telepresence is a function of both technology and perceiver. (Steuer, 1992,p.10)

Content and interaction design for integrating either AR or VR into ROCs will require emphasis on human factors, as the applicability of AR/VR to teleoperations relies on human perceptions (vision, auditory, touch, force feedback, smell), with vision playing a dominant role (Slater & Sanchez-Vives, 2016). Thus, operation time, efficiency and safety rely on the operator's degree of visual ability (Pladere et al., 2022), as this is known to impact human tolerance of AR/VR head-mounted displays (HMDs).

In this context, we find that the virtual replication of a physical asset, its systems, and the robots in a Digital Twin (DT) could help mediate autonomous robot operations and the need for direct telepresence control. With two-way cyber-physical communication (Figure 11), users might engage with the robots and process system and related IMR tasks (Kaarlela et al., 2023). The use of DTs in this and in the context of remote IMR and related support to onsite IMR deserves further investigation, as it might limit some of the complexities associated with the use of robots, given that their autonomous capabilities will be strengthened in the future. This may provide a more 'user-friendly' interface for work compared to telepresence in most IMR-related tasks.

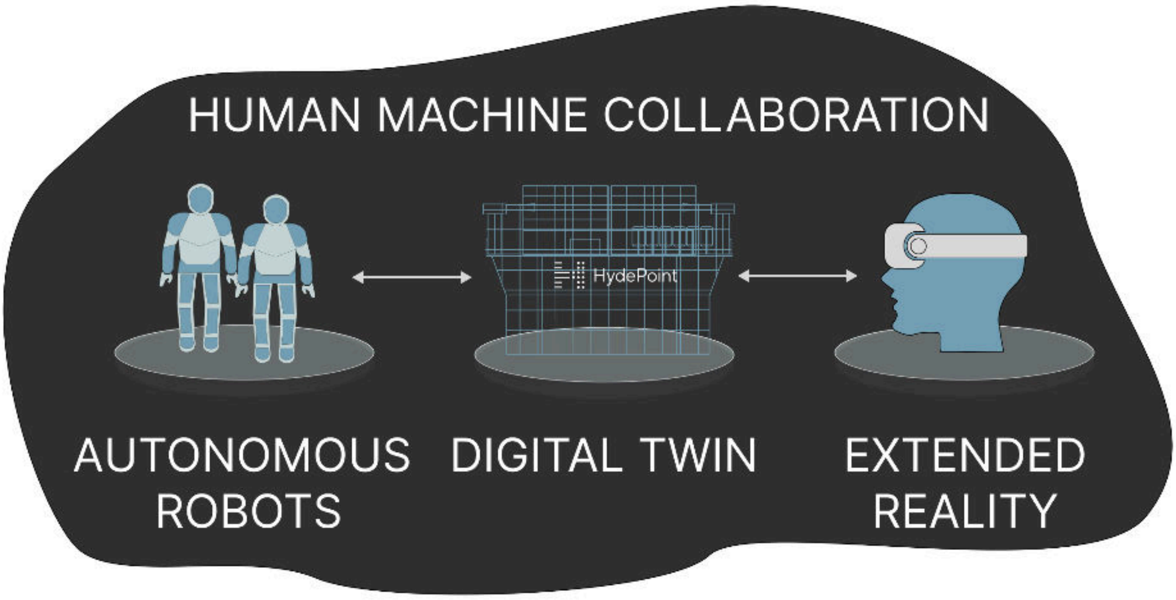

Figure 11: Illustration of technologies that could support the future of IMR in offshore hydrogen substations, where digital twins play a key role in future human-machine collaboration (Strange, 2023).

Exploring a future design philosophy

Through VRLP and by using a SOD approach, we managed to explore the relations among climate change; the renewable energy transition and its safety, costs, efficiency and sustainability aspects; and the importance of IMR in this context, and we touched on technology that could enable such future remote IMR operations. As intended with the VRLP, we are now in a position where new actors are emerging, and new questions are extending the value of offshore hydrogen and the operational and technical value of remote and unmanned operations from a sociotechnical perspective. Key challenges to consider are the temporal problems related to the development and adoption of technology and its related uses. Again, we use telepresence and XR in general as rich examples, as visual ability can play an explicit role in determining who might be the optimal operator of the ROC, which can moderate human operators' responses and, therefore, enable the effective and safe use of AR/VR HMDss.

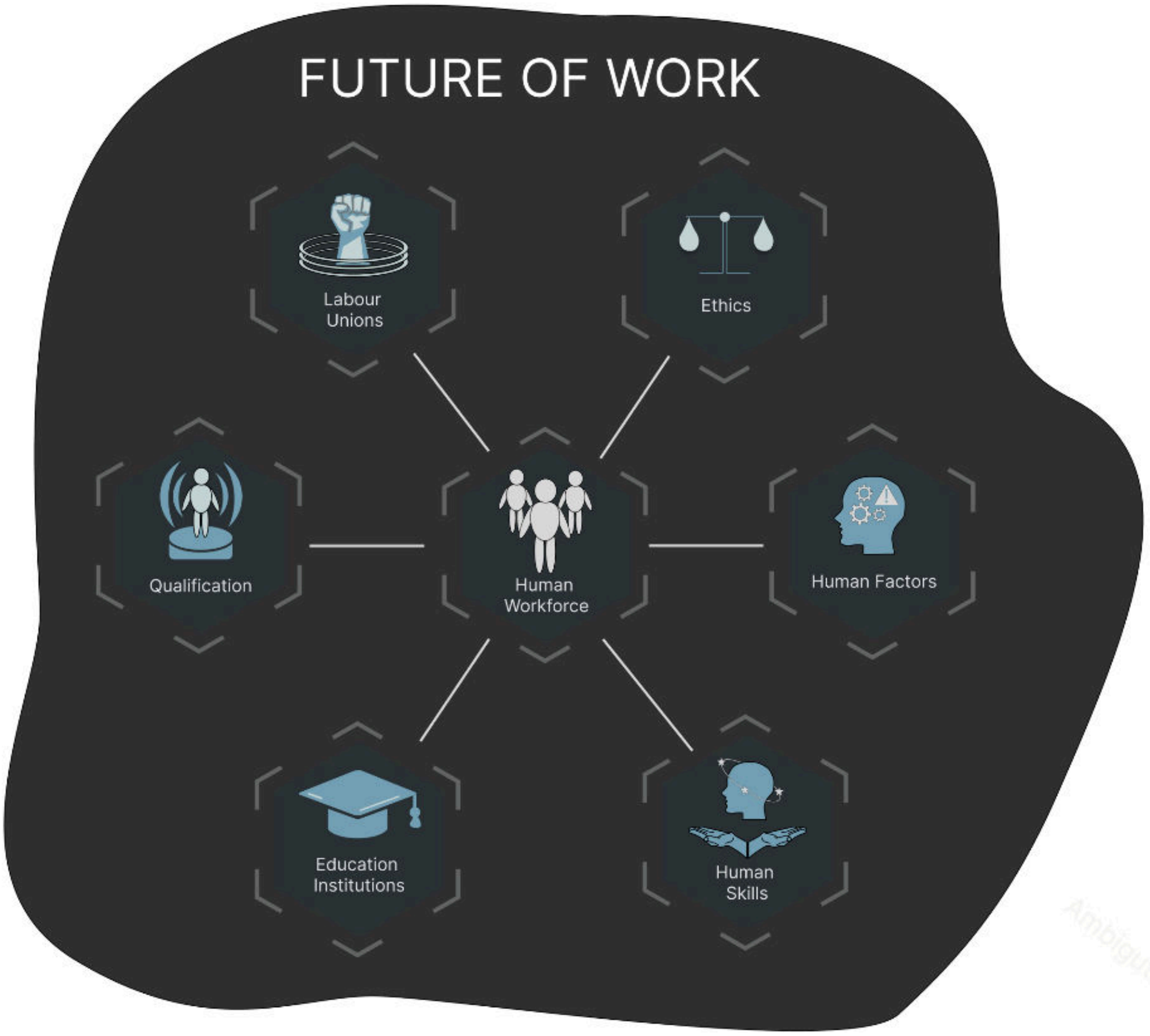

Figure 12: Illustrations of new perspectives that could support the establishment of a design philosophy and foster a broader industrial debate on the future of work in our case (Strange, 2023).

Hence, we see that integrating XR technologies into complex systems, such as the case study described in this paper, requires human factors to be broadened beyond what is currently described, including reflections on equitable, inclusive and human-centred design (Boyd-Noronha, 2020; Davis et al., 2021; Fox & Thornton, 2022; Friedman & Kahn, 2000). Looking also at HRI and DTs, we ask what social relations non-human robotic entities and autonomous systems will evoke and what regulations should apply to such IMR operations. Further, who would be eligible to work and interact with these systems, robots and operations and what prerequisites in terms of skill set, education and mental and physical health would be necessary?

In our further work, we will address a set of new perspectives (Figure 10) that will influence the human-centred design of the Hydepoint operation and explore it through more detailed experiments to understand better how it can be structured to achieve the design philosophy underlying the overarching work. A philosophy can be used in further research to foster additional learning and participatory industrial debate.

Conclusions

We consider the VRLP approach successful for its original purpose: to achieve a superficial yet relevant systematic understanding of the system, and it is sufficient to create empathy for different stakeholder perspectives and to establish a foundation for stakeholder communications and further research topics (Sevaldson, 2022). We argue further that similar projects to Hydepoint will benefit from a related process to uncover anticipated complexities and challenges well ahead of its first operation, thus revealing the need to broaden human factors beyond what is currently described. Thus, we propose to outline a design philosophy for an inclusive, safe, human-centric future of work in the context of IMR in offshore renewable energy.

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Additional information

Please note that Kongsberg Maritime AS is part of a shared ownership in the newly established company Hydepoint, and that this paper has used Hydepoint as a case study given the access to information about the operation provided in workshops and interviews. The goal of the paper has been to connect and collect multiple perspectives, such as business, engineering, operations, robotics, systemic design, design research and optic research, into a paper that can be presented, shared, and distributed openly to foster debate and possible interventions. We aim to set focus on the importance of beginning early to address inclusivity and human-centric design for maintenance in remote and autonomous offshore energy operations. Please reach out to any of the authors if you have further questions.