Towards Industry 5.0

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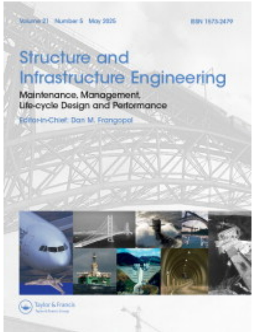

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Towards Industry 5.0: a stakeholder analysis to understand the human role in the adoption of a heritage bridge human-centric digital twin framework

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ABSTRACT

The adoption of a novel industry paradigm is an *untamed* problem that requires strong social consensus and involves a high degree of technological uncertainty. To solve this problem a multi-actor engagement and agreement are needed. In this article, the methodology and the findings obtained after conducting a stakeholder analysis to understand how different actors could work together towards the adoption of Industry 5.0 principles and enabling technologies are presented. The analysis has been framed within a case study dealing with the conservation of historical bridges in the city of Oslo, Norway. The education institutions of the city were assumed as the *problem owners*. This research indicates that the Ministry of Transport and the Ministry of Climate and Environment, along with their subordinate agencies (Statens Vegvesen and Riksantikvaren, respectively) together with Oslo Kommune and its Cultural Heritage Office, possess the critical financial and regulatory resources necessary for adopting this paradigm. Their leadership and capacity to mobilise resources are pivotal in incentivising other stakeholders. Such resources should be driven towards a suitable business model, the adoption of human-centric digital twins as enabling technology, the establishment of interdisciplinary collaborations between the identified stakeholders, and the up-skilling/re-skilling of the industry workforce.

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Bridges; built cultural heritage environment; conservation; digital twins; human-centrism; Industry 5.0; resilience; sustainability

1. Introduction

The concept of Industry 4.0 has driven increased industrial digitalisation and higher productivity. In recent times, the field of bridge engineering has greatly benefitted from technological advancements associated with Industry 4.0 (Chacón et al., 2024, 2025; Jiang et al., 2023; Shim et al., 2019). These include the use of Digital Twins (DTs) and Building Information Modeling (BIM) to enhance bridge management (Tita et al., 2023), the application of DT for enriched structural health monitoring of bridges and other infrastructure assets (Pillai et al., 2022), the opportune damage detection and early warning notification to bridge operators through a DT (Hagen & Andersen, 2024), the utilisation of DT to aid during the construction process of bridges (Hu et al., 2022), the implementation of advanced anomaly detection algorithms to optimise the management and operation of bridges within a DT framework (Jiménez Rios et al., 2023a), among others. For an in-depth discussion on current technological advances in bridge engineering, and in particular on the improved damage detection, monitoring, modelling, and their influence on the bridge management decision-making process, one can consult the comprehensive review conducted by Martins et al. (2024).

Nevertheless, Industry 4.0 has also brought about unanticipated challenges (European Commission, 2020). These challenges include the environmental impact of intensified industrial activities (United Nations, 2023) and the potential risks posed by an increasingly automated industrial system to the human element within the socio-economic chain (Ellingrud et al., 2023). Regrettably, as emphasised in the United Nations (UN) Emissions Gap Report 2022 (United Nations, 2022), insufficient action has been taken so far to address the global climate crisis. It has been recently reported that since 2020, the progress towards the achievement of UN Sustainability Development Goals (SDGs) has stagnated, and 84% of the set targets show either limited or reversal progress (Sachs et al., 2024). There is an urgent need for a rapid transformation in the energy supply, industry, transport, and buildings sectors to meet the goals of the Paris Agreement (United Nations, 2015). This transformation is also supported by the European Union (EU) and promoted through the European Green Deal (EGD) (European Commission, 2019).

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Consequently, Industry 4.0 is now considered insufficient to achieve EU goals by 2030 (European Commission, 2022), leading to the emergence of a new paradigm, Industry 5.0, primarily built upon three core principles (European Commission, 2021): human-centrism, resilience, and sustainability. DTs and simulations have been recognised as one of the key enabling technologies of this transformative vision.

Despite being a relatively recent concept, Industry 5.0 has quickly attracted the interest of many researchers. In-depth analysis of its fundamental principles and the technologies that could make it possible have been conducted (Adel, 2022; Choi et al., 2022; Maddikunta et al., 2022). Adel (2022) has discussed the role and challenges posed by collaborative robots, blockchain, internet of things, big data analytics, DTs, and 6 G along with their recent applications on manufacturing, supply chain, and healthcare. Choi et al. (2022) argued about the radical changes that technologies such as 3D printing, internet of things, blockchain, and DTs have brought about in the field of operations management. Furthermore, they have proposed a so-called 'sustainable social welfare' which according to those authors may be suitable to reconcile any potential conflicts between humans and machines within the novel Industry 5.0 paradigm.

Whereas that Maddikunta et al. (2022) have surveyed Industry 5.0 technologies with the potential of increasing production levels and delivering customised products, among which are edge computing, blockchain, collaborative robots, internet of things, DTs, and 6 G. Additionally, researchers have put forth fresh frameworks for its application (Mourtzis et al., 2022; Turner & Garn, 2022; Yang et al., 2022) and have begun to create practical applications across various domains, including manufacturing (Wang et al., 2023), education (Ruppert et al., 2022), data privacy (Sasikumar et al., 2023), food security (Guruswamy et al., 2022), and wind energy infrastructure (Chen et al., 2021).

However, it is worth noting that the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry has yet to explore, let alone implement, Industry 5.0 principles and enabling technologies. As noted by Jiménez Rios et al. (2024) DTs and artificial intelligence are two of the most extensively explored technologies in this domain. Among the principles of Industry 5.0, sustainability emerges as the most widely discussed aspect in the current body of literature. Resilience and human-centrism require further proactive efforts to be fully integrated into the industry's conservation practices to achieve a balanced adoption of the three foundational principles proposed by Industry 5.0.

This article is an extended version of a recent conference paper (Jiménez Rios et al., 2024). The work presented herein considers the increasingly important role that humans will have within existing bridge DT frameworks and how Industry 5.0 principles and enabling technologies could be better implemented within this perspective. Thus, a stakeholder analysis was performed to understand how different actors could work together towards the adoption of Industry 5.0 principles and enabling technologies. The rest of this manuscript is organised as follows: background information is presented in section 2, the details of the methodology followed is presented in section 3, the obtained findings and a thorough discussion are presented thereafter in section 4, and finally, the drawn conclusions and future work are highlighted in section 5 of the manuscript.

2. Background

Most bridges in Europe were constructed during the second half of the twentieth century. Many of them have deteriorated and are approaching the end of their service life since their original design lifespan was typically 50–100 years, (Gkoumas et al., 2021). Wenzel has estimated that 10% of existing bridges suffer from structural deficiencies (Wenzel, 2009). This has been evidenced in recent years by the structural failure of several bridges, being the collapse of the Morandi Bridge in Genova, Italy, perhaps the most unfortunate one among these incidents by the number of victims and the amount of economic losses caused (Malerba, 2024). From another point of view, there are several European bridges considered historical structures holding significant cultural value. Seven bridges in particular stand out from the rest as they are part of the United Nations Educational, Scientific and Cultural Organisation (UNESCO) World Heritage List (UNESCO WHC, 2023) (see Figure 1). The damage or collapse of a historical bridge causes the irreplaceable loss of a cultural asset along with the human and economic losses linked to the disturbance on the transportation network they are a key part of.

The development and adoption of DT is particularly noteworthy to various stakeholders in the AECMO&C industry. DTs are virtual replicas of physical assets capable of real-time performance monitoring and the early identification of potential issues, ultimately enhancing safety and reducing maintenance costs (Schleich et al., 2017). Within the context of cultural heritage bridges, DT can also be used to validate the proposal of novel intervention techniques (Jiménez Rios & O'Dwyer, 2019; Zampieri et al., 2023) before they are applied in the asset, thus preventing incompatibility damages.

The consensus in the industry is strong, as there is widespread agreement on the value of DT for all phases of the life cycle of bridges, including design, construction, management, operation, and decommissioning/conservation. Furthermore, DTs have been the object of study in several research projects funded by the EU and are considered to have the potential to influence the development of enhanced bridge inspection and monitoring practices (Gkoumas et al., 2024). Nevertheless, creating Industry 4.0 DTs presents several significant challenges, among which, i) the lack of compatibility among various proprietary and open-source software used in the DT model generation process, ii) the lack of consensus regarding the development of macro-DT that combine DT models of individual assets, and iii) the absence of Findable, Accessible, Interoperable, and Reusable (FAIR) (Wilkinson et al., 2016) benchmark databases

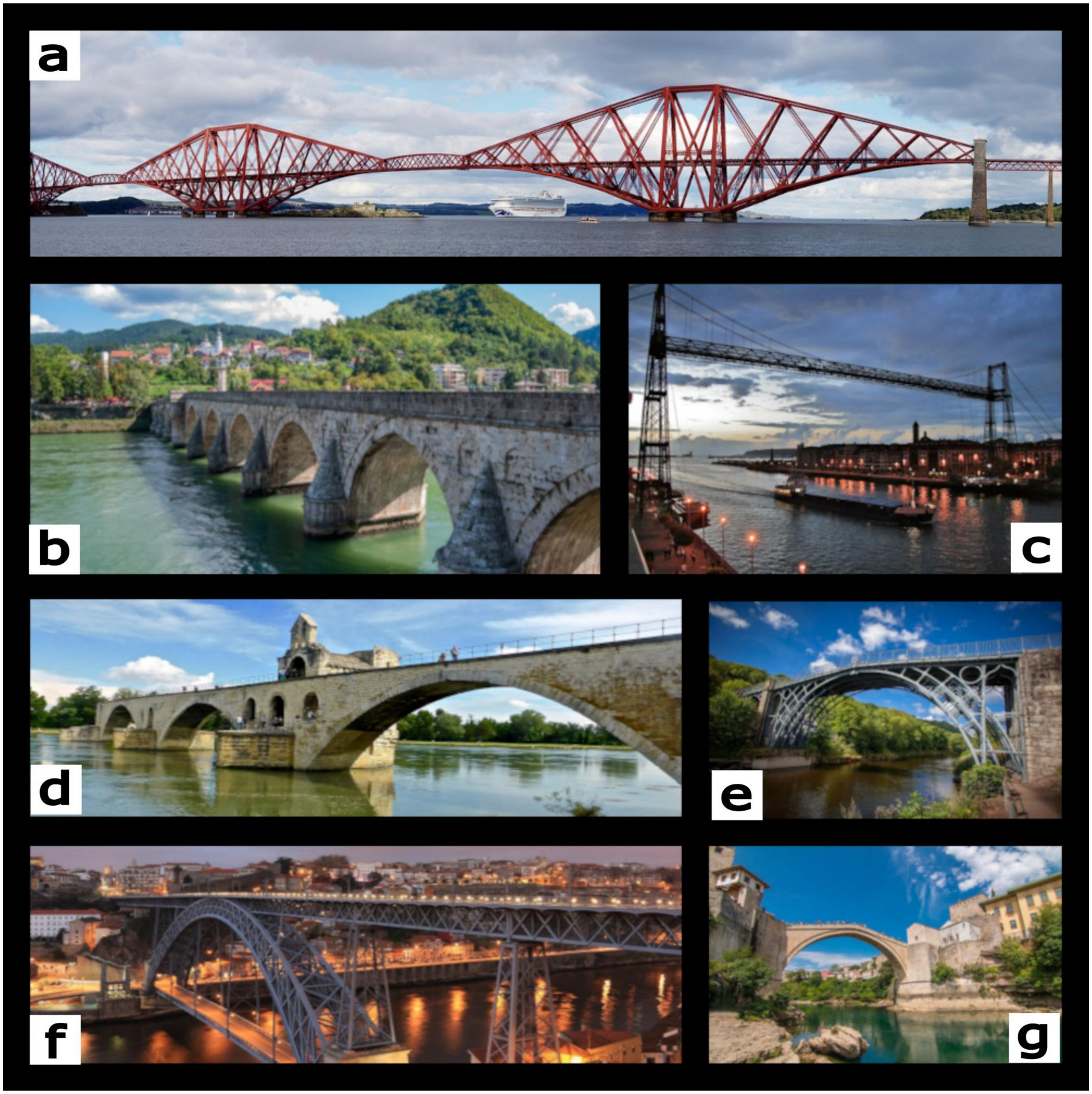

Figure 1. European bridges part of the UNESCO World heritage List: (a) the forth bridge located in the United Kingdom of great britain and Northern Ireland, (b) the mehmed paša sokolović bridge of višegrad located in Bosnia And Herzegovina, (c) vizcaya bridge located in Spain, (d) avignon bridge located in France, (e) ironbridge gorge located in the United Kingdom of great britain and Northern Ireland, (f) luiz I bridge located in Portugal, and (g) stari most (old bridge) located in Bosnia And Herzegovina.

suitable for prototyping and validating DTs (Jiménez Rios et al., 2023b, 2023c).

While conservation professionals recognise the importance of Industry 5.0 principles and technologies, addressing knowledge gaps, improving training, and securing resources are crucial steps for overcoming current barriers. These measures are essential for the successful adoption of this new paradigm and for fully realising its benefits (Jiménez Rios et al., 2024). A plausible framework for Industry 5.0 principles implementation is the one proposed by an augmented DT, also referred to as a human-centric DT (HCDT) (see Figure 2). In this novel framework, an additional 'human asset' (besides the Industry 4.0 components corresponding to the 'physical asset' and 'digital asset') component is considered. This component is composed of a series of digital technologies capable of enhancing human stakeholders' performances, which could ultimately result in a sustainable and resilient built environment. The different digital tools proposed include exoskeletons, augmented reality, virtual reality, wearable trackers, intelligent personal assistants, collaborative robots, social networks, and big data analytics, all of which have been thoroughly discussed elsewhere (Mourtzis et al., 2022).

The adoption of Industry 5.0 principles and HCDTs offers a transformative approach to addressing the limitations observed in traditional Industry 4.0-based DTs within the built cultural heritage sector. By integrating the 'human asset' into the DT framework, HCDTs introduce digital

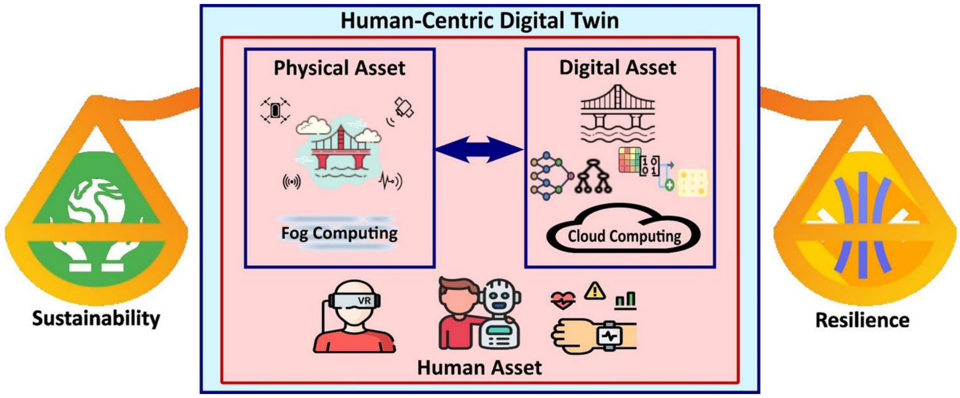

Figure 2. Novel Industry 5.0 human-centric digital twin framework.

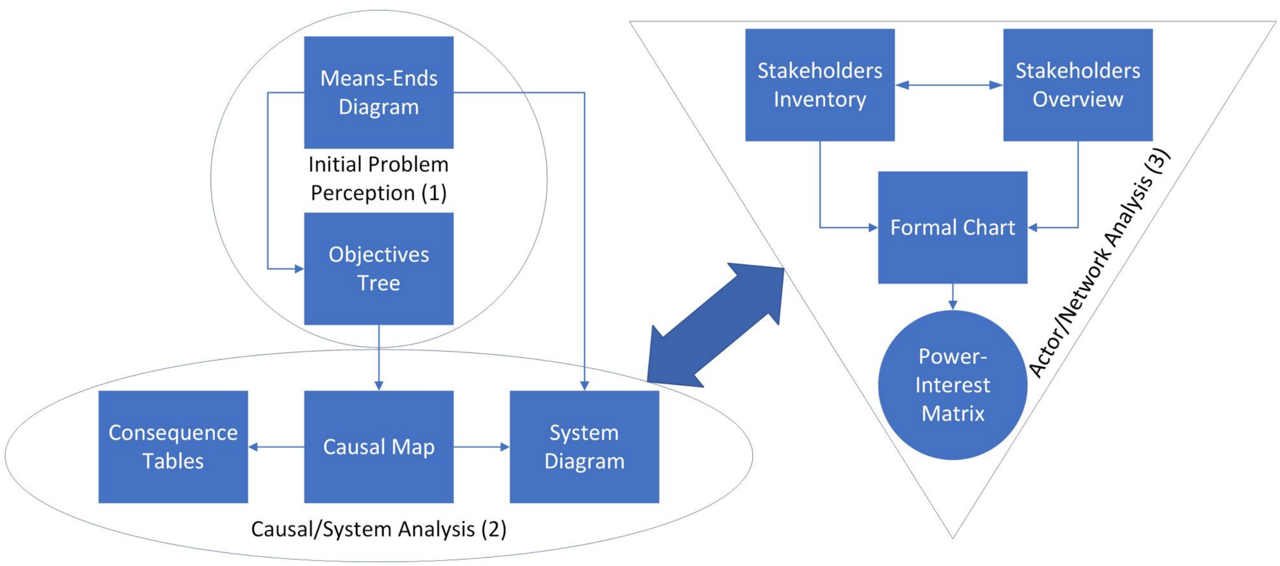

Figure 3. Overall methodology workflow followed. Numbers between brackets indicate the time sequence. Double headed arrows indicate mutual influence between stages.

technologies that enhance human decision-making and collaboration, facilitating better stakeholder engagement and performance. This human-centric component fosters greater interoperability, addressing the first issue of compatibility between proprietary and open-source software by promoting standards-driven, human-guided platforms that prioritise ease of integration. Furthermore, the concept of HCDTs inherently supports the development of macro-DTs by enabling seamless collaboration between stakeholders across different domains, thus fostering consensus and the convergence of DT models into cohesive macro-level representations. Finally, the alignment of HCDTs with FAIR principles directly contributes to the creation of accessible and reusable benchmark databases, enabling improved prototyping and validation of DTs for cultural heritage conservation.

3. Methodology

The adoption of a novel industry paradigm could be described as an 'untamed' problem as it requires strong social consensus and involves a high degree of technological uncertainty (van de Graaf & Hoppe, 1996). Thus, to solve this problem a multi-actor engagement and agreement are needed. A system analysis approach is a useful tool that provides insights and helps to analyse complex problems, such as is the adoption of Industry 5.0 principles by different stakeholders of the AECMO&C industry. Therefore, in this work, the methodology on policy analysis of multi-actor systems developed by Enserink et al. (2022) has been followed to conduct a stakeholder analysis and better understand the human role in the adoption of a HCDT framework.

This methodology was applied in a case study focused on the conservation of cultural heritage bridges in Oslo, Norway, where the city's educational institutions were identified as the primary *problem owners*. Our attention focuses primarily on Oslo Metropolitan University (OsloMet, through its Department of Built Environment) and on the Oslo School of Architecture and Design (AHO), which are the two stakeholders in Oslo offering educational programs specialised in the AECMO&C industry. The overall methodology workflow followed is shown in Figure 3 and each sub-stage conducted is further detailed in the next subsections.

3.1. Problem formulation and system analysis

The first step in the policy analysis of multi-actor systems consists of clearly formulating the problem at hand through the construction and interpretation of a means-ends diagram. Thus, a means-end diagram was built starting by identifying a dissatisfaction about an actual situation (as exposed in the introduction of this work), followed by the creation of a verb sentence that expressed the desired situation (the *end*). Then a series of consecutive 'why' questions related to the identified desired situation were asked. Answers were placed in rectangles linked through arrows (pointing upwards). When no meaningful answer could be given any more, a backpropagation process started asking 'how' each one of the identified ends could be achieved (the *means*). This process provided a comprehensive view of the situation and helped to select, together with appropriate spatial and temporal demarcations, an adequate level of analysis. This methodology enabled us to explore a broad spectrum, from concrete fundamentals to abstract concepts, and from foundational principles to specific actions.

The selected problem was then rewritten in the form of a focal objective 'noun' phrase. As the focal objective obtained from the means-ends diagram usually has an abstract nature or involves different complex aspects, it must be further refined by means of an objectives tree. Objectives trees help to simplify the problem by operationalising it into lower-level objectives and providing measurable criteria parameters. This tool was created using noun phrases to describe the objectives while avoiding confusion with the *means* of the previously described diagram and ensuring that each objective had either zero or more than one sub-objective. Finally, the lowest level of objectives was operationalised by assigning measurable criteria to each factor.

Once the problem had been clearly defined and the factors related to it identified and operationalised, the effect of each factor in the system outcome (and on other factors) could be qualitatively observed through a causal relation diagram, also known as a causal map. A causal map links means to criteria, and it is built by asking 'Which factors influence X criteria?'. To keep the causal map useful and relatively easy to interpret, the number of elements on it has been limited to a maximum of twenty as suggested by Enserink et al. (2022). Further analysis of the factors affecting system means other than the implementation of enabling technologies is outside the scope of this work. Moreover, only factors that can change have been included in the causal map developed, whereas constants have been discarded. Links between elements in the causal map are represented by arrows, which are labelled either with a '+' or '- 'sign, denoting increments (positive relation) or decrements (negative relation), respectively.

Means-end diagram, objectives tree, and the casual map are all summarised in a system diagram. Within this holistic tool, the path between means and external factors can be traced to qualitatively assess their influence on the system criteria. Furthermore, the system diagram allows us to visualise the problem boundaries and internal factors interactions within the system. This is an important step within the performed stakeholder analysis as a system diagram can be used for communication purposes among the different agents involved. As indicated by Enserink et al. (2022) the identified means have been placed at the left boundary of the diagram, external factors at the top boundary, and criteria at the right edge of the system. To ease the interpretation of the system diagram, and of the inter-factor interactions depicted within it, the findings were summarised in consequence tables. One consequence table groups the effects of different means on the system criteria, whereas a second table indicates the effects of external variable factors on the criteria.

3.2. Actor analysis

The following step consisted of the creation of a stakeholders' inventory. Within the context of the created system, a stakeholder, or an actor is defined as *a person, an organisation, or a social entity able to act on or exert influence on a decision*. Such *decisions* are taken within a certain *arena*, a concept which is understood as *a dedicated social space for strategic decision-making* (Enserink et al., 2022) within the context of an stakeholder analysis. Two different actor identification techniques were followed, so that, although partially overlapping, individual results could complement each other. The techniques followed were: i) positional approach where actors were identified based on their formal position in policymaking, and ii) opinion leadership approach where stakeholders with an influence on others were identified and included. According to a recommendation in the literature (Enserink et al., 2022), between ten to twenty stakeholders were included in the analysis.

Stakeholders' information on rights, responsibilities, and organisational charts along with established procedures, legislation, and laws, was collected to draw a formal chart. In this chart, it was possible to visualise the mutual relations between different stakeholders and to sketch the arena within which they could interact to solve the problem under study. The different stakeholders included in the inventory were placed in the formal chart following an intuitive vertical hierarchy. Relationships among actors of interest were represented with labelled arrows which indicated formal relations between corresponding stakeholders. To avoid cluttering in the chart, only those relations considered important were drawn.

The main characteristics of the inventoried stakeholders were then studied based on their interests, objectives, and perceptions. In this context, interests represent stakeholders' matters of importance and point towards a fixed direction, objectives are dynamic and indicate stakeholders' wishes under the current problem context, and perceptions are stakeholders' interpretations of the situation. A stakeholder overview table tool was developed and extended with each stakeholders' resources and importance, qualitatively classified as low, medium, or high, as well as replaceability, namely, whether they could be replaced or not by redundant actors. Finally, with all the information collected and based on a systematic comparison, stakeholders' dependencies were determined. Such dependencies were assessed based both on the level of importance of the resources held by a particular actor and on whether they could be replaced by alternative resources. Consequently, critical actors, either by their action capabilities or by their blocking power, were identified. In the end, stakeholders' interdependencies were summarised and presented in the form of a power-interest grid.

4. Results and discussion

4.1. Means-ends diagram

The means-ends diagram developed to support the system delimitation for the study case selected is presented in Figure 4. Its construction started by asking the question: Why should Industry 5.0 principles be adopted? Plausible answers to this question led to a series of desired positive outcomes among which are the achievement of emissions neutrality, the increment of industry competitiveness, and the improvement of working conditions for the AECMO&C industry workforce, among others.

A second iteration of 'why' questioning (i.e. why is the achievement of emissions neutrality desired? Why should industry competitiveness be increased? and so on) led to the end of generating economic, ecologic, and societal value. The inherent benefits of generating these series of positive values were considered as the upper level of the developed means-ends diagram. But what are the means needed for the adoption of Industry 5.0 principles? In other words, how can the adoption of Industry 5.0 be achieved? According to our analysis, this problem could be tackled if efforts are directed in four different directions: i) the modification of current business models, ii) the investment in enabling technologies (mainly in the implementation of the discussed HCDT), iii) the establishment of interdisciplinary collaborations between diverse stakeholders, and iv) the up skilling/re-skilling of the AECMO&C industry workforce.

The interpretation of the means-ends diagram created helps clearly describe the gap and problem dilemma. Thus, the problem under study can now be rewritten in the form of a focal objective such as 'Adoption of sustainability, resilience, and human-centrism'. This objective should be achieved while aiming at avoiding a series of undesirable side effects. A key issue for our study case is the hampering of technology development. Therefore, the problem dilemma is defined as: 'How can the problem owner achieve a successful adoption of the Industry 5.0 paradigm' (the 'end') through the implementation of the novel HCDT without (undesirable side effects of the means immediately below 'end'), hampering technology development nor leading to unsympathetic and incompatible intervention on the conservation practices of cultural heritage bridges? Furthermore, this useful tool has assisted in the problem's spatial demarcation, which for the case study presented in this article has been limited to the city of Oslo, Norway, as well as its temporal demarcation, a successful adoption of Industry 5.0 is aimed to be achieved by 2030.

4.2. Objectives tree

An objective tree was created (see Figure 5) to identify the outcomes of interest in achieving the focal objective through the implementation of HCDT. These items were formulated as measurable criteria that the higher educational institutions in the city aim to provide to society. Namely, high return on investment [profit/initial cost], high regulatory compliance [days/regulatory approval], low energy consumption [watts/hour], high acceptance [perception level], and many jobs generated [jobs generated/year]. This analysis is limited to the implementation of enabling technologies to achieve a successful implementation of the Industry 5.0 paradigm. Similar objective trees could be created by operationalising the remaining means identified (e.g. the modification of current business models, etc.), thus providing a holistic view of the system. That development is out of the scope of this work.

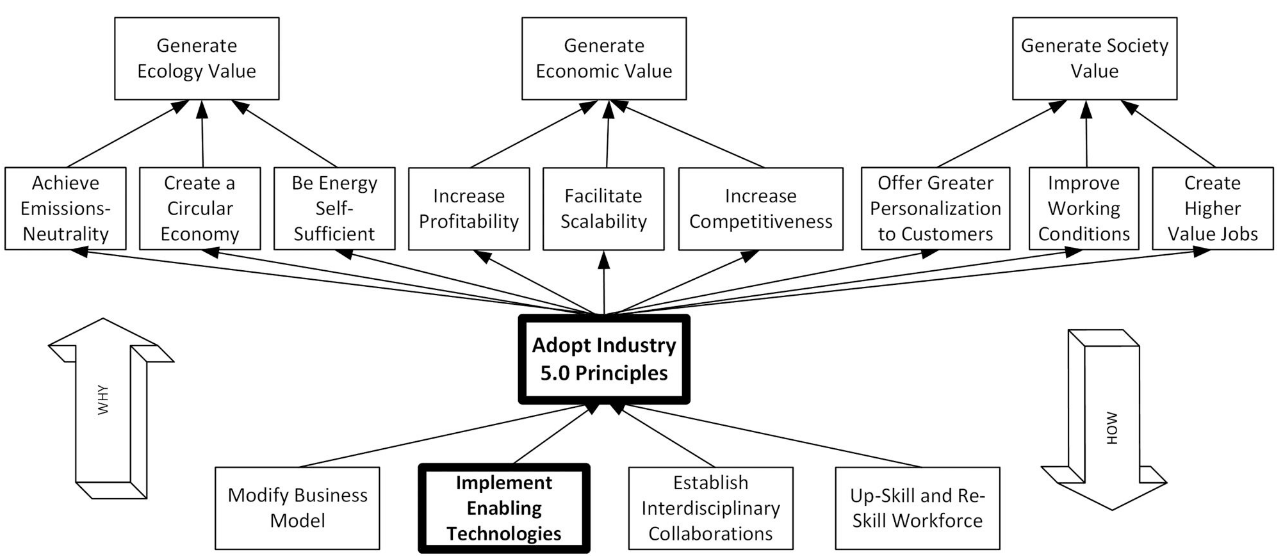

Figure 4. Means-ends diagram on the adoption of industry 5.0 (it is not limited to the study case under discussion, but it is of general application character).

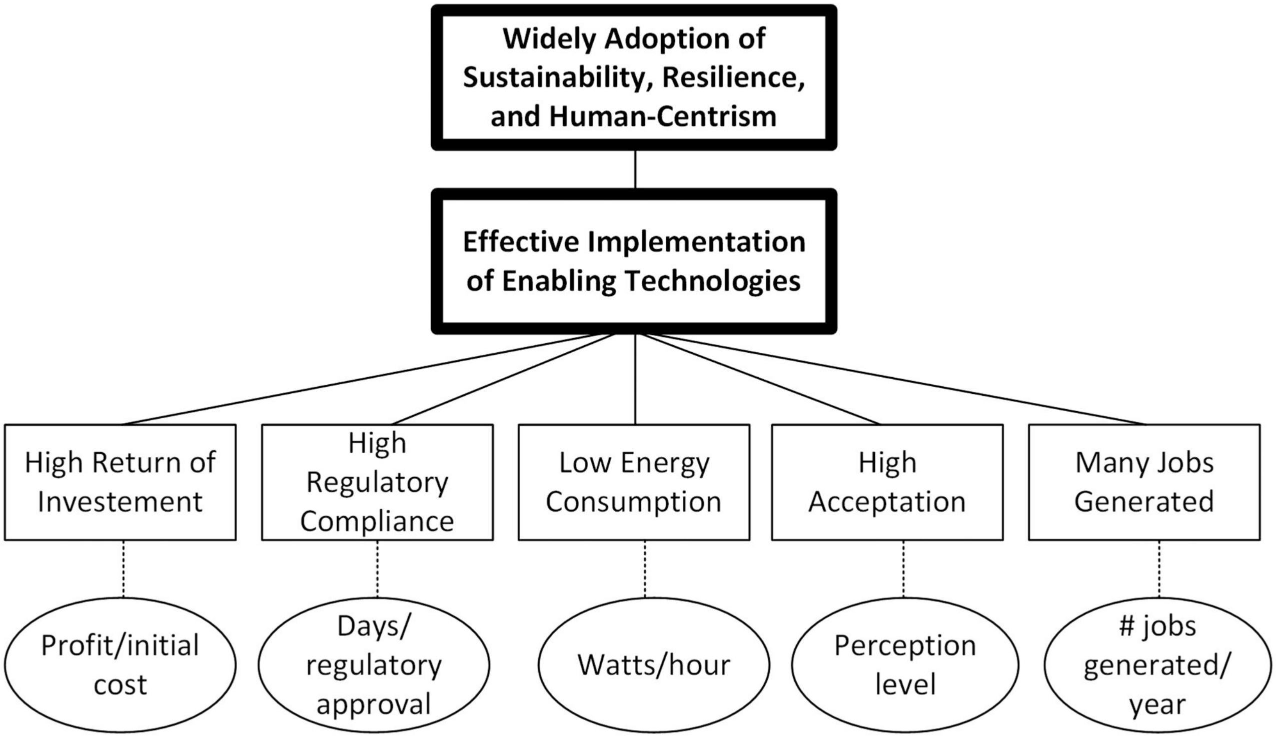

Figure 5. Objectives tree used to simplify and operationalise the case study problem.

4.3. Causal map

The relationship between system factors and identified measurable criteria is better understood through a causal map, like the one presented in Figure 6. The causal map allows us to conduct a more systematic search of the effects any relevant factors may have in the criteria of interest. By questioning 'How can the problem owner change X? for each factor X, the analyst may reveal what factors are connected to which criteria. At this stage, other factors considered relevant have been added to the system.

It is worth noting that, only dynamic factors are included within the presented causal map, whereas constant factors have been left out, as stakeholders cannot modify them even if desired. For instance, the 'security' factor which is of paramount importance to be considered within the Industry 5.0 paradigm, may lead to a higher level of acceptance of this transformative vision, while at the same time may complicate the achievement of compliance with regulatory frameworks, due to the increased number of considerations that would need to be met on a further digitalised framework, as the one proposed by the HCDT discussed.

4.4. System diagram

A system diagram presented in Figure 7 depicting a conceptual model of the analysed case study, was created by combining the information from the means-end diagram (Figure 4) and that of the casual map (Figure 6). In this diagram a more elaborate structure of the problem can be observed. Means are placed on the left side of the boundary, external factors are located at the top, whereas criteria of interest are located at the right border of the system diagram.

The implementation of enabling technologies and their effect on internal system factors and the identified criterion was the focus of attention. The path from means to criteria is qualitatively assessed based on the arrow connectivity and sign. To facilitate the interpretation of the system diagram, the causal pathways are tabulated in consequence tables. Table 1 tracks the implementation of enabling technologies as the object of interest in the analysis and presents the causal pathways from external factors to measurable criteria. From these results, it can be observed that the adoption of Industry 5.0 principles by the educational institutions of the city would bring with it higher complications to comply with regulatory frameworks.

Moreover, such regulations may not even be in place now, but are under development, such as the recently approved European Union legislation on Artificial Intelligence (Madiega, 2023). It can also be said that initially, the adoption of Industry 5.0 principles would negatively affect the return on investment of the problem owners. Nevertheless, it has been shown that early adoptions require small monetary investments, whereas to maintain competitiveness, later adopters require higher amounts of investment (Della Seta et al., 2012).

Conversely, return on investment could be benefitted by the incentives provided by the government, although it may be reduced due to the fluctuating costs of electricity. On the other hand, positive impacts are expected in terms of job generation and perception level both by implementation of Industry 5.0 enabling technologies as by government incentives. Whereas the energy consumption criteria would

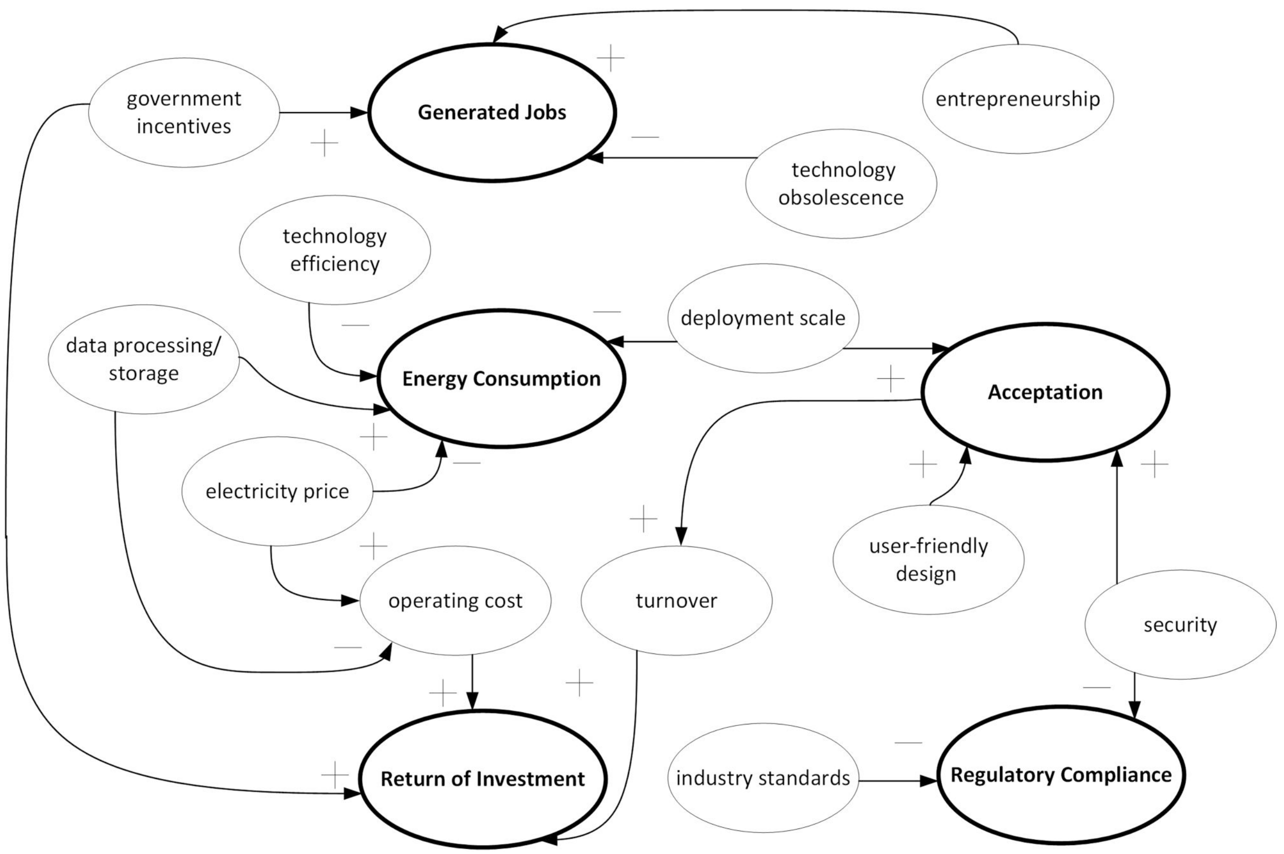

Figure 6. Causal map showing relations between factors and identified criteria. Note: a '+' denotes a positive relation (meaning that if the value of the identified mean increases, the value of the corresponding criteria will also increase), and a '–' denotes a negative relation (if the value of the identified mean increases, the value of the corresponding criteria will decrease).

Table 1. Consequence table on the implementation of enabling technologies for the identified system means and external factors.

Means/criteria	Return of investment	Generated jobs	Acceptation	Energy consumption	Regulatory compliance
Implementation of Enabling Technologies	+, +, −	−, −	+, +	+, −, and +, +	+, −
Government incentives	+	+	+		
Electricity price	+,–			–	

Note: a '+' denotes a positive relation (meaning that if the value of the identified mean increases, the value of the corresponding criteria will also increase), and a '–' denotes a negative relation (if the value of the identified mean increases, the value of the corresponding criteria will decrease).

receive mixed inputs. From one point of view, enhanced technological efficiency would reduce the amount of energy consumption. These criteria would be further impacted negatively by the external electricity prices in the market, which fluctuates unpredictably. The proposed HCDT technology would require great amounts of data processing/storage, which would ultimately be reflected in a higher energy consumption as well.

4.5. Stakeholders inventory

The adoption of such an important paradigm shift is a complex problem that cannot be fixed in isolation by the problem owner itself. Therefore, an inventory of relevant stakeholders that may contribute to reaching a solution was created. Stakeholders at international, regional, national, and local levels (see Figure 8a) were identified and clustered by their issues of interest in governance, infrastructure, conservation, education/R&D, industry, and society, as presented in Figure 8b.

This stakeholder mapping is only a subset of those actors considered in a first instance as of relevance ('able to act on or exert influence on a decision'). The number has been limited to less than twenty actors according to an accepted rule of thumb (Enserink et al., 2022). The inclusion of some actors within the inventory was relatively straightforward, namely, Statens Vegvesen (Norwegian Public Roads Administration) and Oslo Kommune (Municipality of Oslo), as these two stakeholders own and operate the existing heritage bridges in the city of Oslo. On the other hand, the inclusion of actors such as ICOMOS or Europa Nostra could be slightly more controversial as, although the interest of these important cultural heritage conservation institutions aligns with the preservation of historical bridges (and other built assets), their direct influence at a local level was not evident at first sight. Nevertheless, significant interaction opportunities among all included stakeholders have been found after an in-depth analysis was conducted and will be discussed hereafter.

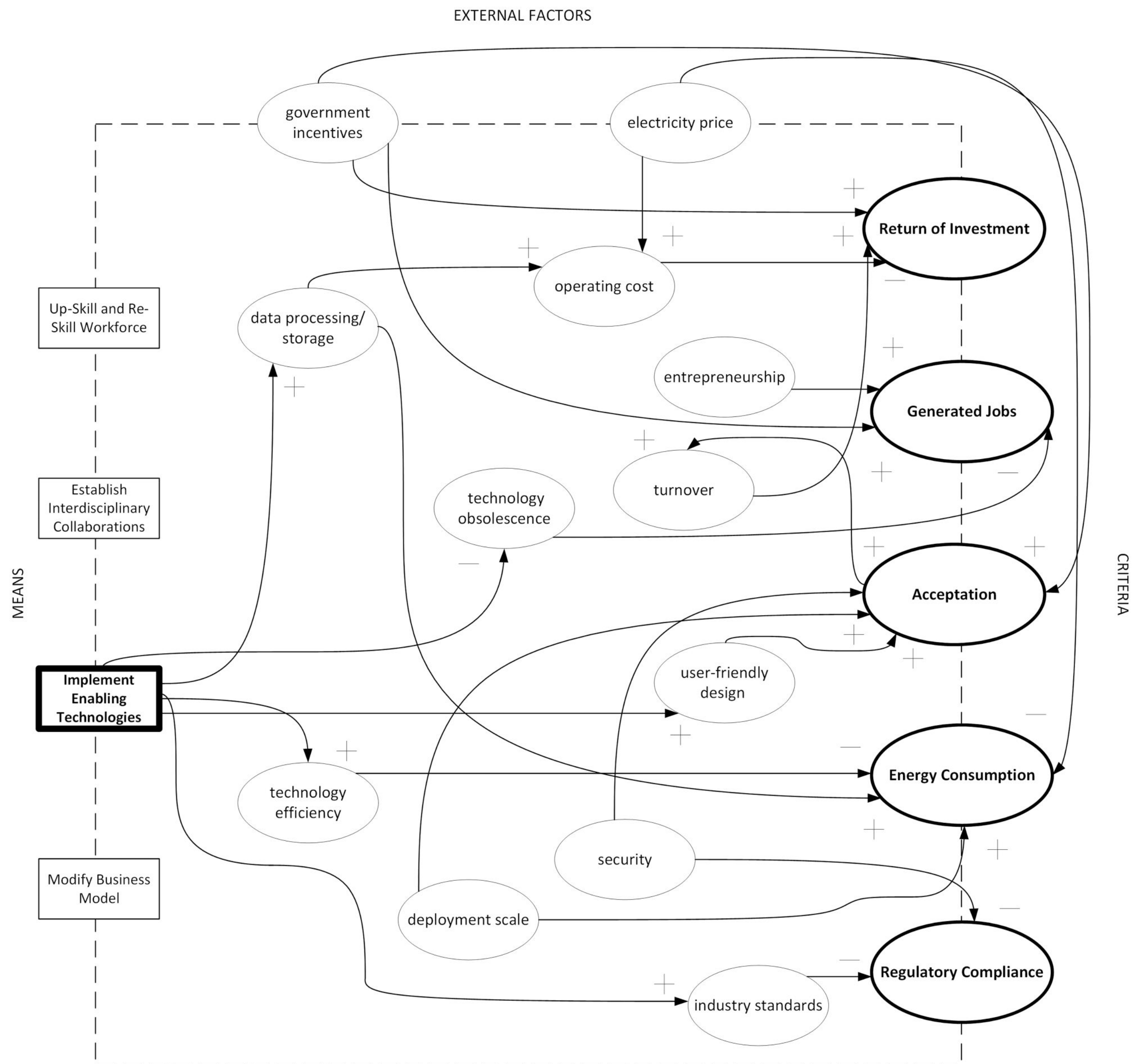

Figure 7. (Sub-)System diagram after amalgamation of means-end diagram and causal map. Note: a '+' denotes a positive relation (meaning that if the value of the identified mean increases, the value of the corresponding criteria will also increase), and a '–' denotes a negative relation (if the value of the identified mean increases, the value of the corresponding criteria will decrease).

4.6. Formal relationships mapping

The key characteristics of the considered stakeholders have been summarised and are presented in Table A1 in the Appendix. By compiling, analysing, and relating the different actors' interests, objectives, perceptions, and resources, the formal relationships among them could be better understood. Those relationships were mapped through a formal chart, as shown in Figures 9.

Our attention focuses primarily on Oslo Metropolitan University (OsloMet, through its Department of Built Environment) and on the Oslo School of Architecture and Design (AHO), which are the two stakeholders in Oslo offering educational programs specialised in the AECMO&C industry. They obtain research funding both from European and National institutions and can participate in the co-creation and delivery of teaching/research projects with two important stakeholders involved in the conservation of cultural heritage: the Norwegian Institute for Cultural Heritage Research (NIKU) and the National Trust of Norway (Fortidsminneforeningen). Both NIKU and Fortidsminneforeningen are guided by the charters, guidelines, and conservation best practices developed by international institutions in the field of conservation, namely, the International Center for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the International Council on Monuments and Sites (ICOMOS).

Interdisciplinary research and professional practices can be performed between the education institutions in the city, key international AECMO&C industry associations (i.e. International Association for Bridge Maintenance and Safety, IABMAS; and the International Association for Bridge and Structural Engineering, IABSE), and the main players in the infrastructure sector at national level (Statens

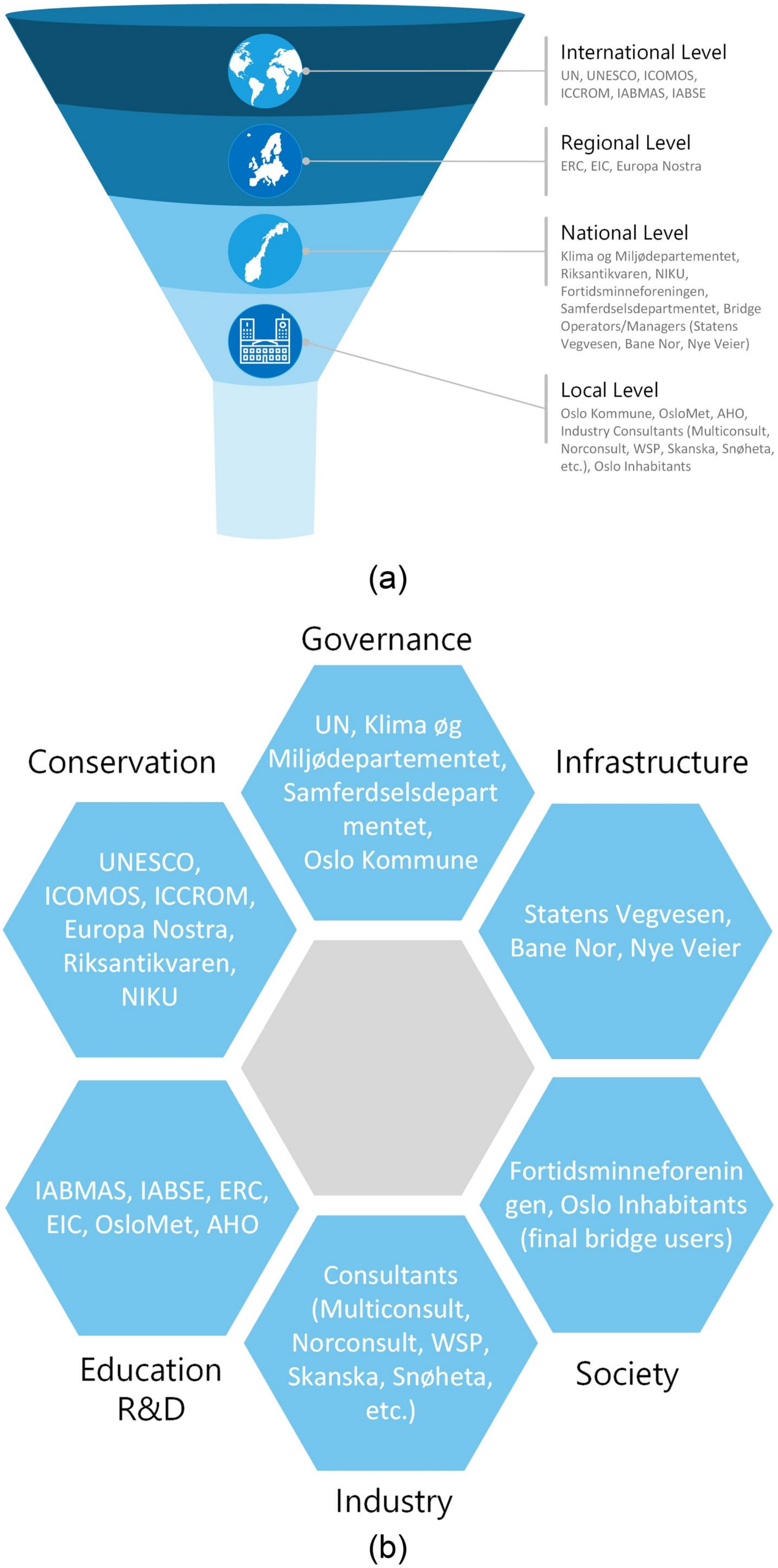

Figure 8. Stakeholders' inventory: (a) classified according to its geographical level of influence and (b) grouped in accordance with their issues of interest (see Table A1 for detailed descriptions of the stakeholders).

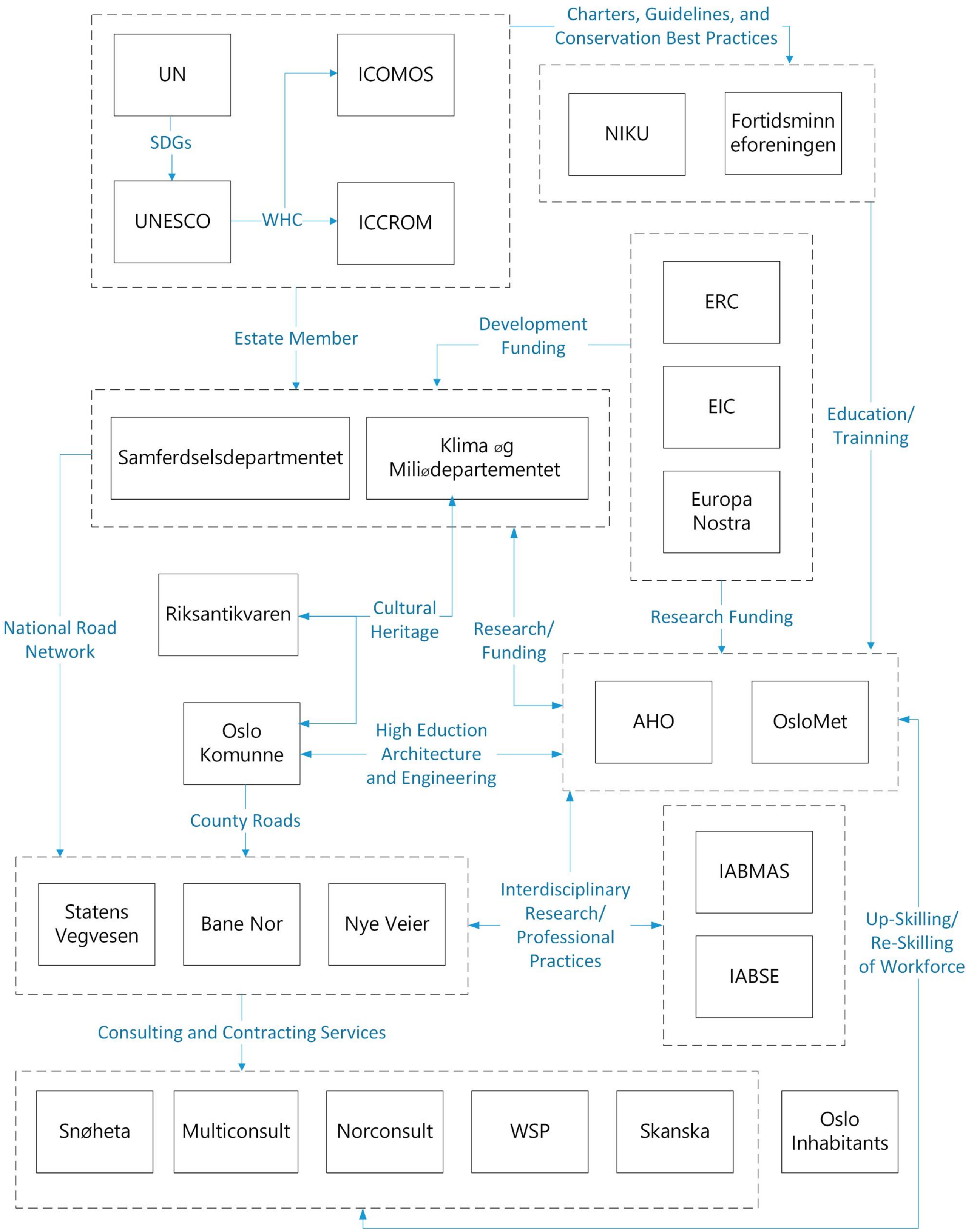

Figure 9. Formal chart of interactions between relevant stakeholders identified.

Vegvesen, who is responsible for the management of two protected bridges in Oslo under the National Conservation Plan for the Norwegian Public Roads Administration) (Klima- og miljødepartementet, 2022). Both governmental Ministries at the national level are bound to comply with international agreements, since Norway is a Member Estate of the UN and UNESCO. The achievement of SDGs is of interest for the former, whereas compliance with World Heritage Convention (WHC) statutory documents and resolutions is of paramount importance for the latter.

Finally, these universities can play a key role in the up-skilling and re-skilling of the AECMO&C industry

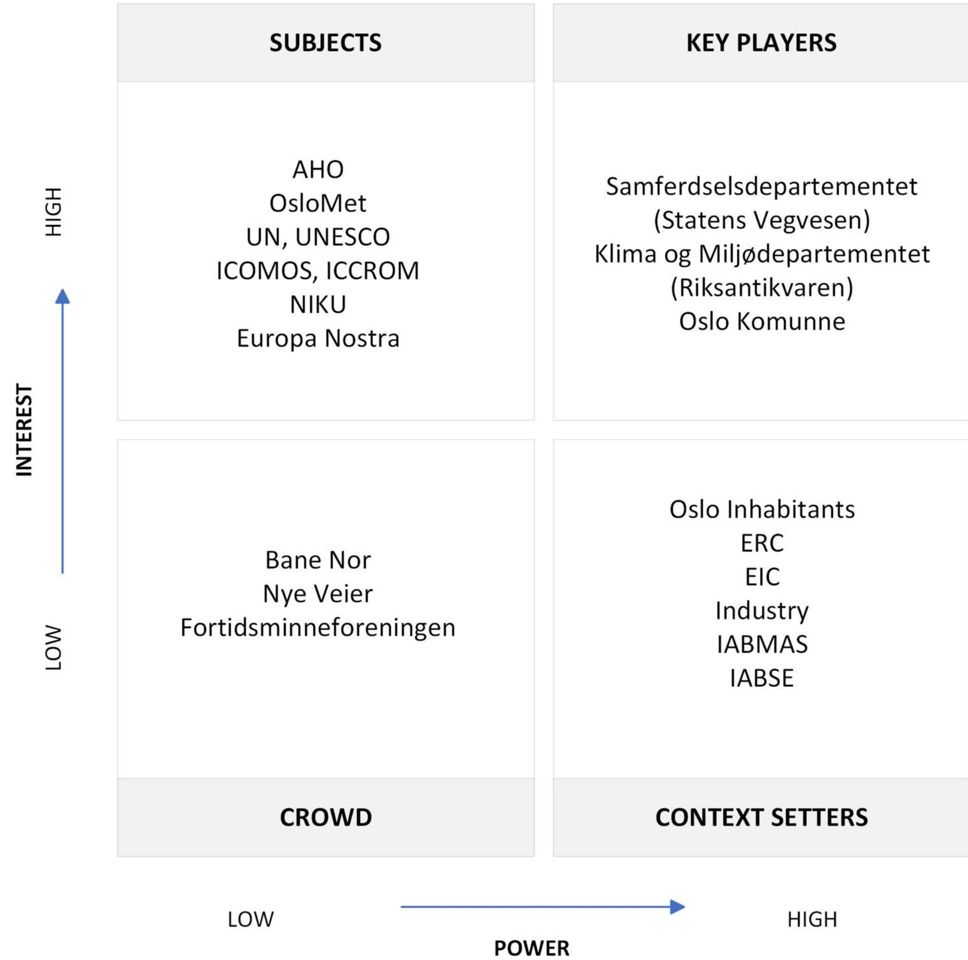

Figure 10. Power-interest matrix used to classify stakeholders based on their level of interest and available power to fix the problem under consideration.

workforce, represented by some consulting and contracting companies in Figures 9. Finally, concerning the inhabitants of the city, it can be said that, although they do not have a direct interrelation with the universities of the city for the conservation of heritage bridges, they are considered end beneficiaries of the cultural heritage conservation and infrastructure development efforts. Their satisfaction is essential for the success of bridge conservation projects.

4.7. Identification of key actors

The last three columns in Table A1 present the assigned level of importance and dependency given to each actor as well as the classification regarding their corresponding replaceability. After conducting a systematic comparison, the key players identified for the adoption of Industry 5.0 principles in the context of conservation of existing bridges with cultural heritage value in Oslo, Norway (see the power-interest matrix presented in Figure 10), are those of governance nature both at national and local level. The Ministry of Transport and the Ministry of Climate and Environment with their subordinate agencies, Statens Vegvesen and Riksantikvaren (The Directorate for Cultural Heritage) respectively, along with Oslo Kommune and its Cultural Heritage Office Agency possess the monetary and authority irreplaceable resources to adopt such principles while incentivising the remaining stakeholders to follow.

These stakeholders satisfy both the 'power of realization' and 'blocking power' criteria. Therefore, the educational institutions in the city cannot ignore them, on the contrary, should aim at strengthening their interrelations with them. It is hypothesised that if such resources are driven towards a suitable business model, the adoption of HCDTs as enabling technology, the establishment of interdisciplinary collaborations between the identified stakeholders, and the up skilling/re-skilling of the AECMO&C industry a successful adoption could be achieved. These efforts would ultimately result in the creation of economic, ecological, and societal value.

5. Conclusions

Industry 5.0 has recently surged as a novel paradigm to tackle the unforeseen negative consequences of its predecessor and is rapidly being adopted in different sectors. In this paper, the human-centrism principle fostered by Industry 5.0 and how it could be better implemented within the context of bridge engineering has been explored. The work was carried out following a six-step stakeholder analysis methodology which was applied in a study case involving the conservation of existing bridges, particularly those with a cultural heritage value, in the city of Oslo, Norway. The educational institutions of the city were assumed to be the *problem owners*.

Overall, the stakeholder analysis conducted has unveiled a multi-layered network of interaction and cooperation needed between international bodies, national and local government agencies, educational and research institutions, infrastructure firms, and the community, to successfully adopt Industry 5.0 principles and enabling technologies for the conservation of historical bridges in the city of Oslo, Norway. Both the Norwegian Ministry of Transport and the Ministry of Climate and Environment with their subordinate agencies, Statens Vegvesen and Riksantikvaren respectively, along with Oslo Kommune and its Cultural Heritage Office Agency possess the monetary and authority irreplaceable resources to adopt such a paradigm while incentivising the remaining stakeholders to follow. Only through multi-actor cooperation and agreement all working together towards sustainable development, cultural heritage preservation, and infrastructure improvement, could the novel Industry 5.0 transformative vision be successfully adopted, and its benefits be observed in the conservation of heritage bridges.

The current practice of conducting periodic bridge inspections on a fixed schedule has proven to be inadequate in preventing the progression of damage between inspections. This reactive approach often leads to the undetected deterioration of critical structural elements, escalating repair costs, and, in extreme cases, catastrophic failures. By adopting an Industry 5.0 HCDT framework, particularly for the conservation of heritage bridges, maintenance strategies could shift from reactive to proactive. HCDTs enable continuous, real-time monitoring of structural health through the integration of advanced digital technologies and human expertise. This would facilitate the timely detection of potential damage, allowing for immediate interventions before further deterioration occurs. Additionally, the human-centric aspect of the HCDT ensures that human stakeholders—engineers, conservators, and decision-makers—are empowered with enhanced data insights and tools for more informed decision-making. Ultimately, this approach promotes the preservation of heritage bridges through more efficient, cost-effective, and sustainable maintenance practices, significantly reducing the risk of unforeseen failures and ensuring long-term resilience.

Despite the pragmatic and systematic nature advantages of stakeholder analysis, it does not come without cons. Some limitations of this methodology include the fact that stakeholder classification is static while in the real world stakeholders evolve constantly and dynamically, its lack of specificity, and the reliability of the information upon which it is constructed (Hermans & Thissen, 2009). Luckily its main drawback could be greatly mitigated through a participatory approach. The involvement of different stakeholders and citizens in scientific research and/or knowledge production through a co-creation workshop, for example, could significantly enhance the outcomes of this kind of work (Fritz et al., 2019).

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References

Adel, A. (2022). Future of industry 5.0 in society: Human-centric solutions, challenges and prospective research areas. *Journal of Cloud Computing*, *11*(1), 40. https://doi.org/10.1186/s13677-022-00314-5

Chacón, R., Casas, J. R., Ramonell, C., Posada, H., Stipanovic, I., & Škarić, S. (2025). Requirements and challenges for infusion of SHM systems within Digital Twin platforms. *Structure and Infrastructure Engineering*, *21*(4), 599–615. https://doi.org/10.1080/15732479.2023.2225486

Chacón, R., Ramonell, C., Posada, H., Sierra, P., Tomar, R., Martínez de la Rosa, C., Rodriguez, A., Koulalis, I., Ioannidis, K., & Wagmeister, S. (2024). Digital twinning during load tests of railway bridges - case study: The high-speed railway network, Extremadura, Spain. *Structure and Infrastructure Engineering*, *20*(7-8), 1105–1119. https://doi.org/10.1080/15732479.2023.2264840

Chen, X., Eder, M. A., Shihavuddin, A. S. M., & Zheng, D. (2021). A human-cyber-physical system toward intelligent wind turbine operation and maintenance. *Sustainability*, *13*(2), 561. https://doi.org/10.3390/su13020561

Choi, T. M., Kumar, S., Yue, X., & Chan, H. L. (2022). Disruptive technologies and operations management in the Industry 4.0 era and beyond. *Production and Operations Management*, *31*(1), 9–31. https://doi.org/10.1111/poms.13622

Della Seta, M., Gryglewicz, S., & Kort, P. M. (2012). Optimal investment in learning-curve technologies. *Journal of Economic Dynamics and Control*, *36*(10), 1462–1476. https://doi.org/10.1016/j.jedc.2012.03.014

Ellingrud, K., Sanghvi, S., Dandona, G. S., Madgavkar, A., Chui, M., White, O., & Hasebe, P. (2023). *Generative AI and the future of work in America*. https://www.mckinsey.com/mgi/our-research/generative-ai-and-the-future-of-work-in-america

Enserink, B., Bots, P., van Daalen, E., Hermans, L., Kortmann, R., Koppenjan, J., Kwakkel, J., Ruijgh, T., Thissen, W., & Slinger, J. (2022). *Policy analysis of multi-actor systems* (2nd ed.). TU Delft OPEN. https://doi.org/10.5074/T.2022.004

European Commission. (2019). *The European Green Deal*. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission. (2020). *Enabling Technologies for Industry 5.0: Results of a workshop with Europe's technology leaders*. https://data.europa.eu/doi/10.2777/082634

European Commission. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*. https://data.europa.eu/doi/10.2777/308407

European Commission. (2022). *Industry 5.0: A transformative vision for Europe*. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-transformative-vision-europe_en

Fritz, S., See, L., Carlson, T., Haklay, M., Oliver, J. L., Fraisl, D., Mondardini, R., Brocklehurst, M., Shanley, L. A., Schade, S., Wehn, U., Abrate, T., Anstee, J., Arnold, S., Billot, M., Campbell, J., Espey, J., Gold, M., Hager, G., He, S., Hepburn, L., Hsu, A., Long, D., Masó, J., McCallum, I., Muniafu, M., Moorthy, I., Obersteiner, M., Parker, A. J., Weissppflug, M., & West, S. (2019). Citizen science and the United Nations Sustainable Development Goals. *Nature Sustainability*, *2*(10), 922–930. https://doi.org/10.1038/s41893-019-0390-3

Gkoumas, K., dos Santos, F. L. M., & Pekar, F. (2021). *Research in bridge maintenance, safety and management: An overview and outlook for Europe* [Paper presentation]. 10th International Conference on Bridge Maintenance, Safety and Management. IABMAS. https://doi.org/10.1201/9780429279119-239

Gkoumas, K., Stepniak, M., Cheimariotis, I., & Marques dos Santos, F. (2024). New technologies for bridge inspection and monitoring: A perspective from European Union research and innovation projects. *Structure and Infrastructure Engineering*, *20*(7–8), 1120–1132. https://doi.org/10.1080/15732479.2024.2311898

Guruswamy, S., Pojić, M., Subramanian, J., Mastilović, J., Sarang, S., Subbanagounder, A., Stojanović, G., & Jeoti, V. (2022). Toward better food security using concepts from Industry 5.0. *Sensors*, *22*(21), 8377. https://doi.org/10.3390/s22218377

Hagen, A., & Andersen, T. M. (2024). Asset management, condition monitoring and Digital Twins: Damage detection and virtual inspection on a reinforced concrete bridge. *Structure and Infrastructure Engineering*, *20*(7–8), 1242–1273. https://doi.org/10.1080/15732479.2024.2311911

Hermans, L. M., & Thissen, W. A. H. (2009). Actor analysis methods and their use for public policy analysts. *European Journal of Operational Research*, *196*(2), 808–818. https://doi.org/10.1016/j.ejor.2008.03.040

Hu, W., Lim, K. Y., & Cai, Y. (2022). Digital twin and Industry 4.0 enablers in building and construction: A survey. *Buildings*, *12*(11), 2004. https://doi.org/10.3390/buildings12112004

Jiang, F., Ding, Y., Song, Y., Geng, F., & Wang, Z. (2023). Digital twin-driven framework for fatigue lifecycle management of steel bridges. *Structure and Infrastructure Engineering*, *19*(12), 1826–1846. https://doi.org/10.1080/15732479.2022.2058563

Jiménez Rios, A., L. Petrou, M., Ramirez, R., Plevris, V., & Nogal, M. (2024). Industry 5.0, towards an enhanced built cultural heritage conservation practice. *Journal of Building Engineering*, *96*, 110542. https://doi.org/10.1016/j.jobe.2024.110542

Jiménez Rios, A., Nogal, M., Plevris, V., Ramirez, R., L., & Petrou, M. (2024). Towards enhanced built cultural heritage conservation practices: Perceptions on Industry 5.0 principles and enabling technologies. *The Historic Environment: Policy & Practice*, *15*(4), 466–492. https://doi.org/10.1080/17567505.2024.2429167

Jiménez Rios, A., & O'Dwyer, D. (2019). External post-tensioning system for the strengthening of historical stone masonry bridges. In Structural *analysis of historical constructions: An interdisciplinary approach*. RILEM Bookseries. https://doi.org/10.1007/978-3-319-99441-3_168

Jiménez Rios, A., Plevris, V., & Nogal, M. (2023a). Bridge management through digital twin-based anomaly detection systems: A systematic review. *Frontiers in Built Environment*, *9*, 1176621. https://doi.org/10.3389/fbuil.2023.1176621

Jiménez Rios, A., Plevris, V., & Nogal, M. (2023b). *Synthetic data generation for the creation of bridge digital twins what-if scenarios* [Paper presentation]. 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN), Athens, Greece. https://doi.org/10.7712/120123.10760.21262

Jiménez Rios, A., Plevris, V., & Nogal, M. (2023c). *Uncertainties in the synthetic data generation for the creation of bridge digital twins* [Paper presentation]. 5th International Conference on Uncertainty Quantification in Computational Science and Engineering (UNCECOMP), Athens, Greece. https://doi.org/10.7712/120223.10323.20020

Jiménez Rios, A., Plevris, V., & Nogal, M. (2024). *Human role in existing bridge digital twin frameworks, towards Industry 5.0*. Bridge Maintenance, Safety, Management, Digitalization and Sustainability (IABMAS2024). https://doi.org/10.1201/9781003483755-87

Klima- og miljødepartementet. (2022). *Forskrift om endring i forskrift om fredning av statens kulturhistoriske eiendommer*. https://lovdata.no/dokument/LTI/forskrift/2022-11-17-1976

Maddikunta, P. K. R., Pham, Q. V., B, P., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications [Review]. *Journal of Industrial Information Integration*, *26*, 100257. https://doi.org/10.1016/j.jii.2021.100257

Madiega, T. (2023). *Artificial intelligence act*. E. P. R. Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698792/EPRS_BRI(2021)698792_EN.pdf

Malerba, P. G. (2024). Bridge vulnerabilities and collapses: The Italian experience. *Structure and Infrastructure Engineering*, *20*(7–8), 976–1001. https://doi.org/10.1080/15732479.2023.2277362

Martins, A. C. P., Franco de Carvalho, J. M., Alvarenga, M. C. S., Oliveira, D. S. D., César Júnior, K. M. L., Ribeiro, J. C. L., Santos, G. S., & Verly, R. C. (2024). Detecting, monitoring and modeling damage within the decision-making process in the context of managing bridges: A review. *Structure and Infrastructure Engineering*, 1–23. https://doi.org/10.1080/15732479.2024.2331103

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2022). Operator 5.0: A survey on enabling technologies and a framework for digital manufacturing based on extended reality. *Journal of Machine Engineering*, *22*(1), 43–69. https://doi.org/10.36897/jme/147160

Mourtzis, D., Panopoulos, N., Angelopoulos, J., Wang, B., & Wang, L. (2022). Human centric platforms for personalized value creation in metaverse. *Journal of Manufacturing Systems*, *65*, 653–659. https://doi.org/10.1016/j.jmsy.2022.11.004

Pillai, S., Iyengar, V., & Pathak, P. (2022). Monitoring structural health using digital twin. In Manisha Vohra (Ed.), *Digital twin technology* (pp. 125–139). https://doi.org/10.1002/9781119842316.ch8

Ruppert, T., Darányi, A., Medvegy, T., Csereklei, D., & Abonyi, J. (2022). Demonstration laboratory of Industry 4.0 retrofitting and operator 4.0 solutions: Education towards Industry 5.0. *Sensors*, *23*(1), 283. https://doi.org/10.3390/s23010283

Sachs, J. D., Lafortune, G., & Fuller, G. (2024). *Sustainable Development Report 2024 The SDGs and the UN summit of the future*. https://s3.amazonaws.com/sustainabledevelopment.report/2024/sustainable-development-report-2024.pdf

Sasikumar, A., Vairavasundaram, S., Kotecha, K., Indragandhi, V., Ravi, L., Selvachandran, G., & Abraham, A. (2023). Blockchain-based trust mechanism for digital twin empowered Industrial Internet of Things. *Future Generation Computer Systems*, *141*, 16–27. https://doi.org/10.1016/j.future.2022.11.002

Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. *CIRP Annals*, *66*(1), 141–144. https://doi.org/10.1016/j.cirp.2017.04.040

Shim, C. S., Dang, N. S., Lon, S., & Jeon, C. H. (2019). Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. *Structure and Infrastructure Engineering*, *15*(10), 1319–1332. https://doi.org/10.1080/15732479.2019.1620789

Tita, E. E., Watanabe, G., Shao, P., & Arii, K. (2023). Development and application of digital twin-BIM technology for bridge management. *Applied Sciences*, *13*(13), 7435. https://doi.org/10.3390/app13137435

Turner, C. J., & Garn, W. (2022). Next generation DES simulation: A research agenda for human centric manufacturing systems. *Journal of Industrial Information Integration*, *28*, 100354. https://doi.org/10.1016/j.jii.2022.100354

UNESCO WHC. (2023). *World Heritage List*. Retrieved August 4, 2024, from http://whc.unesco.org/en/list/

United Nations. (2015). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement

United Nations. (2022). *Emissions Gap Report 2022*. https://www.unep.org/resources/emissions-gap-report-2022

United Nations. (2023). *The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 Synthesis Report: Climate Change 2023*. https://www.ipcc.ch/report/ar6/syr/

van de Graaf, H., & Hoppe, R. (1996). *Beleid en Politiek. Een Inleiding tot de Beleidswetenschap en de Beleidskunde*. Coutinho. https://hdl.handle.net/11245/1.127073

Wang, H., Lv, L., Li, X., Li, H., Leng, J., Zhang, Y., Thomson, V., Liu, G., Wen, X., Sun, C., & Luo, G. (2023). A safety management approach for Industry 5.0′s human-centered manufacturing based on digital twin. *Journal of Manufacturing Systems*, *66*, 1–12. https://doi.org/10.1016/j.jmsy.2022.11.013

Wenzel, H. (2009). *Health monitoring of bridges*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470740170

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., & Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 160018. https://doi.org/10.1038/sdata.2016.18

Yang, C., Tu, X., Autiosalo, J., Ala-Laurinaho, R., Mattila, J., Salminen, P., & Tammi, K. (2022). Extended reality application framework for a digital-twin-based smart crane. *Applied Sciences (Switzerland)*, *12*(12), 6030. https://doi.org/10.3390/app12126030

Zampieri, P., Piazzon, R., Ferroni, R., & Pellegrino, C. (2023). The application of external post-tensioning system to a damage masonry arch. *Procedia Structural Integrity*, *44*, 605–609. https://doi.org/10.1016/j.prostr.2023.01.079