*Bridge Maintenance, Safety, Management, Digitalization and Sustainability –
Jensen, Frangopol & Schmidt (eds)*

Human role in existing bridge digital twin frameworks, towards Industry 5.0

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ABSTRACT: Regardless of the current challenges and limitations of Digital Twins, there seems to be only one school of thought and a consensus toward their future adoption for design, construction, management, operation, and decommissioning of bridges. This novel paradigm surged within the Industry 4.0 context and was fostered by evolving technologies such as artificial intelligence, internet of things, big data, among others. Digital twins have now been recognized as an enabling technology towards the development and adoption of Industry 5.0 principles. Such principles are human-centrism, resilience, and sustainability. In this paper we explore the increasingly important role that humans will have within existing bridge digital twin frameworks and how the human-centrism principle could be better implemented within such context. Moreover, we also discuss how a successful implementation of human centrism could uphold and maximize the resilience and sustainability of existing bridges, especially those with cultural heritage value.

1 INTRODUCTION

Most bridges in Europe were constructed after 1945. Originally designed with a lifespan of 50-100 years, many have already begun to deteriorate (Gkoumas et al., 2021). In fact, it is estimated that 10% of these bridges suffer from structural deficiencies (Wenzel, 2009). On another note, numerous historic European bridges hold significant cultural value, with seven of them being listed on the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage List (UNESCO WHC, 2023). Besides the human and economic losses, the damage or collapse of a historical bridge also signifies the painful loss of a cultural asset.

In recent times, the field of bridge engineering has greatly benefited from technological advancements associated with Industry 4.0. These include the use of digital twins (DT) 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 utilization of DT to aid during the construction process of bridges (Hu et al., 2022), the implementation of advanced anomaly detection algorithms to optimize the management and operation of bridges within a DT framework (Jiménez Rios et al., 2023a), among others.

As observed by the non-exhausting list of examples mentioned, the development and adoption of DT is particularly noteworthy to various stakeholders in the Architecture, Engineering, Construction, Management, Operation, and Conservation (AECMO&C) industry. DT 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 as well 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.

DOI: 10.1201/9781003483755-87

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. Nevertheless, creating Industry 4.0 DT 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) 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 suitable for prototyping and validating digital twins (Jiménez Rios et al., 2023b, 2023c).

While the concept of Industry 4.0 has driven an increased industrial digitalization and higher productivity, it 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 emphasized 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. 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).

Consequently, Industry 4.0 is now considered insufficient to achieve European 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): i) human-centrism, resilience, and sustainability. Moreover, DT and simulations have been recognized 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. They have conducted in-depth analysis of its fundamental principles and the technologies that make it possible (Maddikunta et al., 2022). Additionally, researchers have put forth fresh frameworks for its application (Yang et al., 2022) and have begun to create practical applications across various domains, including manufacturing, education, data privacy, food security, and wind energy infrastructure (Chen et al., 2021). However, it's worth noting that the AECMO&C industry has yet to explore, let alone implement, Industry 5.0 principles.

A plausible framework for Industry 5.0 principles implementation is the one proposed by an augmented digital twin, also referred to as a human-centric digital twin (see Figure 1). In this novel framework, an additional "human asset" (besides from the Industry 4.0 components corresponding to the "physical asset" and "digital asset") component is considered. This component is composed by the series of digital technologies capable of enhancing human stakeholders' performances, which could ultimately result into 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).

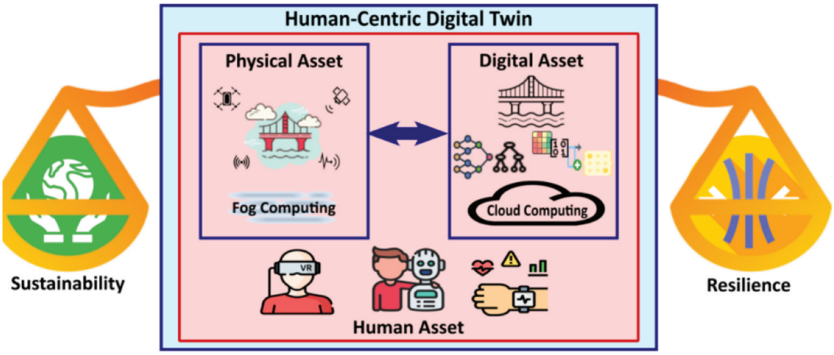

Figure 1. Novel Industry 5.0 Human-Centric digital twin framework.

In this paper, we explore the increasingly important role that humans will have within existing bridge DT frameworks and how the human-centrism principle could be better implemented within such context. We carried out a six-steps stakeholder analysis and discuss how a successful implementation of human centrism could uphold and maximize the resilience and sustainability of existing bridges, especially those with cultural heritage value.

2 METHODOLOGY

A system analysis approach has been applied to analyze the complex adoption of Industry 5.0 principles by different stakeholders of the AECMO&C industry. The stakeholder analysis method proposed by Enserik et al. (Enserink et al., 2022) has been followed. More specifically, this methodology has been implemented in a study case involving the conservation of existing bridges, in particular those with a cultural heritage value, in the city of Oslo, Norway. The case study presented assumes the educational institutions of the city to be the "*problem owners*".

The problem was first clearly formulated through the construction and interpretation of a means-ends diagram. A means-ends diagram was built by first identifying a dissatisfaction about an actual situation. A verb sentence was used to expresses the desired situation (end). Then a series of consecutive "why" questions related to the identified desired situation were asked. Answers were again placed in rectangles linked through arrows (pointing upwards). When no meaningful answer could be given anymore, a "back propagation" process started asking "how" each one of the identified ends could be achieved (means). This process allowed to map a comprehensive view of the situation and helped to select, together with appropriate spatial and temporal demarcations, an adequate level of analysis. The selected problem was then re-written in the form of a focal objective, which was no longer a "verb" phrase, but a "noun" one.

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 the means of an objectives tree. Objectives trees help to simplify the problem by operationalizing it into lower-level objectives and providing measurable criteria parameters. Once the problem has been defined and the factors related to it identified, the effect of each factor in the outcome (and in other factors) can be qualitatively observed through a causal relation diagram, also known as a causal map. Means-ends analysis, objectives tree, and the casual map are all summarized by the means of a system diagram. The path between means and external factors was traced to qualitatively assess their influence in the system criteria. Such influences were summarized in consequence tables.

The following step was to create an inventory of involved stakeholders. To do this, two different 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. Stakeholders' information on rights, responsibilities, and organizational charts along with established procedures, legislation, and laws, was collected to draw a formal chart. In this chart it was possible to visualize the mutual relations between different stakeholders and to sketch the arena within which they could interact to solve the problem under study.

The main characteristics of the inventoried stakeholders were then studied based on their interests, objectives, and perceptions. In this context, interests represent stakeholder's matters of importance and point towards a fixed direction, objectives are dynamic and indicate stakeholders wishes under the current problem context, and perceptions are stakeholder's interpretations of the situation. A stakeholder overview table tool was developed and extended with each stakeholders' resources, importance, and replaceability level. With all this information and based on a systematic comparison, stakeholders' dependencies were determined, and finally presented in the form of a power-interest grid.

3 RESULTS AND DISCUSSION

The adoption of Industry 5.0 principles could be described as an "*untamed*" problem in the classification proposed by (van de Graaf & Hoppe, 1996) as it requires a large degree of social consensus and involves a high degree of technological uncertainty. Thus, this problem requires a multi-actor engagement and agreement to be solved. Why should Industry 5.0 principles be adopted? This question leads to a series of positive outcomes among which are the achievement of emissions neutrality, to increase industry competitiveness, and to improve working conditions. Ultimately, the question "why all these should be done?" leads to the end of generating economic, ecologic, and societal value. But what are the means needed for the adoption of Industry 5.0 principles? According to our analysis, this problem could be tackled if efforts are put in four different aspects: i) the modification of current business models, ii) the investment on enabling technologies (mainly in the implementation of the discussed human-centric digital twin), iii) the establishment of interdisciplinary collaborations between diverse stakeholders, and iv) the up-skilling/re-skilling of the AECMO&C industry workforce. The means-ends diagram developed to support the system delimitation for the study case selected is presented in Figure 2.

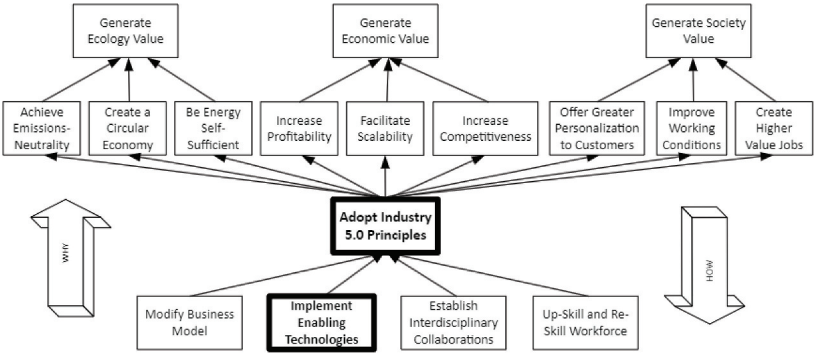

Figure 2. Means-Ends diagram on the adoption of industry 5.0 (It is not limited to the study case under discussion, But it is of general application character).

We can now re-write the problem under study in the form of a focal objective such as that we obtain "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. An objective tree was created (not shown here for the sake of brevity) to identify the outcomes of interest on achieving this focal objective through the implementation of human-centric digital twins. These items were formulated as measurable criteria. Namely, high return of investment [profit/initial cost], high regulatory compliance [days/regulatory approval], low energy consumption [watts/hour], high acceptation [perception level], many jobs generated [jobs generated/year].

The relationship between means (see Figure 2) and identified measurable criteria was better understood thanks to the creation of a causal map (not shown here for the sake of brevity). Eventually, both means-end diagram and casual map were used to depict a conceptual model of the study case analyzed through a system diagram, as presented in Figure 3. In this diagram a more elaborated structure of the problem can be observed. Means are placed in the left side of the boundary. We focus our attention on the implementation of enabling technologies (i.e. human-centric digital twins, the detail analysis of the remaining means is outside of the scope of this paper) and their effect on internal system factors and the identified criteria, which are placed on the right border of the diagram. The path from means to criteria is qualitatively assessed based on the arrow connectivity and sign. These causal pathways are tabulated in the consequence table shown in Table 1.

Table 1. Consequence table on the implementation of enabling technologies for the case under study.

Means/Criteria	Return of Investment	Generated Jobs	Acceptation	Energy Consumption	Regulatory Compliance
Implement Enabling Technologies	+, +, -	-, -	+, +	+, - and +, +	+, -

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 being under development, such as the discussed 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 of investment of the problem owners. Nevertheless, it has been shown that early adoptions require of small monetary investments, whereas that to maintain competitiveness, later adopters require higher amounts of investment (Della Seta et al., 2012). On the other hand, positive impacts are expected in terms of job generation and perception level. Whereas that the energy consumption criteria would receive mixed inputs. From one point of view, an enhanced technological efficiency would reduce the amount of energy consumption. The proposed human-centric digital twin technology would require great amounts of data processing/storages, which would ultimately be reflected on a higher energy consumption.

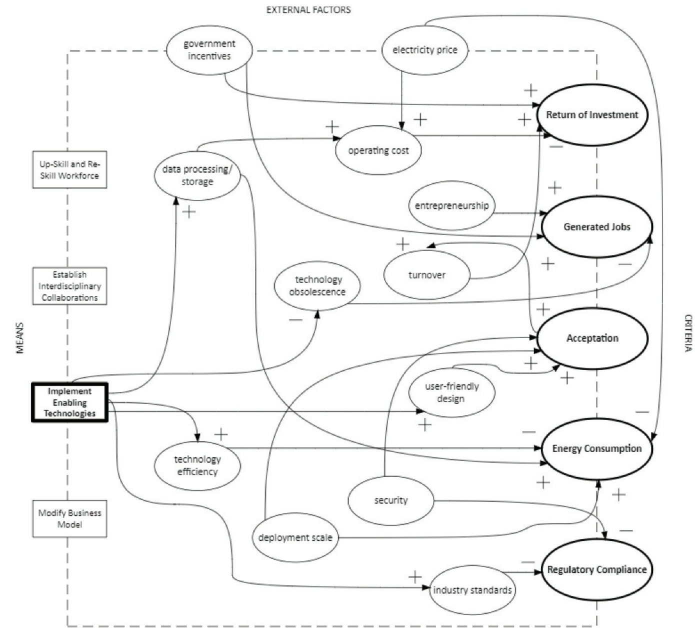

Figure 3. System diagram.

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 which may contribute to reach a solution was created. Stakeholders at international (lately discarded as deemed irrelevant for the case study), regional, national, and local level were identified and clustered in accordance with their issues of interest into governance, infrastructure, conservation, education/R&D, industry, and society. More importantly, the formal relationships among them were map through a formal chart, as shown in Figure 4.

The two stakeholders in Oslo offering educational programs specialized on the AECMO&C industry, and considered on this study, are Oslo Metropolitan University (OsloMet, through its Department of Built Environment) and the Oslo School of Architecture and Design (AHO). 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). Interdisciplinary research and professional practices can be performed between these education institutions and the main players in the infrastructure sector at national level (Statens 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). Finally, these Universities can play a key role in the up-skilling and re-skilling of the AECMO&C industry workforce (represented by some consulting and contracting companies in Figure 4).

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 Figure 5), 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 respectively, along with Oslo Komunne and its Cultural Heritage Office Agency possess the monetary and authority irreplaceable resources to adopt such principles while incentivizing the remaining stakeholders to follow.

It is hypothesized that if such resources are driven towards a suitable business model, the adoption of human-centric digital twins as enable technology, the establishment of interdisciplinary collaborations between the identified stakeholders, and the up-skilling/re-skilling of the

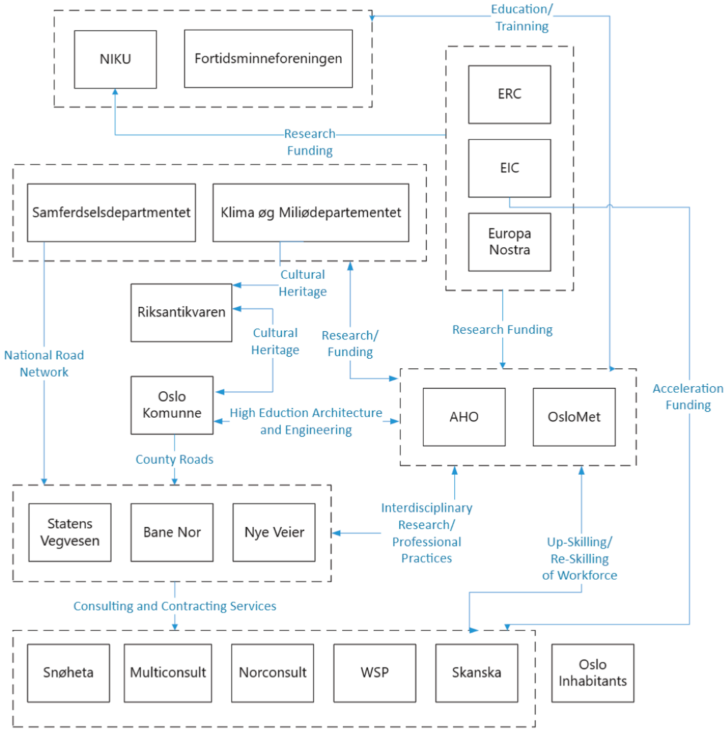

Figure 4. Formal chart.

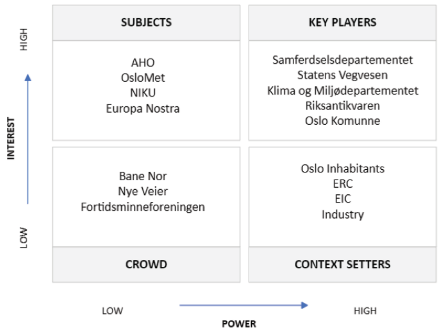

Figure 5. Power-Interest matrix.

AECMO&C industry a successful adoption could be achieved. These efforts would ultimately result in the creation of economic, ecological, and societal value.

4 CONCLUSION

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, we explored how the human-centrism principle fostered by Industry 5.0 could be better implemented within the context of bridge engineering. The work was carried out following a six-steps stakeholder analysis methodology which was applied in a study case involving the conservation of existing bridges, in particular 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*".

Despite of 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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