Decision-making and digital transformation in asset management at Infraestruturas de Portugal

João Duarte Pacheco Clara

Instituto Superior Técnico, December 2021

Decision making is a central topic within asset management in rail and road infrastructure organizations. The decision-making process needs information that is promptly available, accurate, complete, timely and in a clear format. In this context, digital transformation has been widely discussed with the objective to optimize the decision-making process and its outcomes.

There are huge opportunities within new technologies available for the implementation of digital transformation in architecture, engineering and construction projects mainly in the operation and maintenance phases. One of the most relevant issues turns out to be the information requirements to support decision-making, as well as the modelling of decision-making processes considering their context, and the intended results.

This study aims to comprehend the applicability of a decision-making model adjusted to asset management activities and to evaluate, explore and simulate its implementation in a specific case at Infraestruturas de Portugal, the possible impacts within the digital transformation of the organization.

This assessment is based on an analysis of the support technologies as well as the information requirements for the decision-making processes involved in the asset management activities of the Várzeas bridge, namely the remaining useful fatigue assessment performed by Infraestruturas de Portugal.

Keywords: Keywords: Asset Management; decision-making; digital transformation; railway bridges, digital twin

1. INTRODUCTION

Construction sector is often described as not particularly dynamic when it comes to potential technological advances. Since this is an industry where information needs to be promptly available and it needs to be accurate, complete, timely and in a clear format that is understandable to its target audience, the industry has been increasingly keen to embrace digital transformation. The success of a construction project strongly depends on information management and the ability to process the entire volume of data, throughout its life cycle. The most prevalent studies focus mainly on information management during the design and construction phases, which despite being critical, are not often a significant part in the whole project. The operation and maintenance phase are the ones that represents the largest percentage of the total project life cycle. The Digital Twin (DT) is the paradigm that has been mentioned by several authors to solve this problem. One of the DT objectives is to enable a bidirectional communication between the physical system and the digital system, allowing their synchronization, through the most varied technologies, such as sensors, cloud computing and artificial intelligence that have been widely implemented in Industry 4.0.

The digital transformation also referred to as Construction 4.0 is triggering the need to control and monitor assets (infrastructures, buildings, bridges, etc.) during their entire life cycle. This necessity creates a line of research regarding the digital transformation of an asset portfolio. The use of Building Information Modelling has been one of the core technologies for the development of digital transformation programmes. BIM is a collaborative methodology for the design, construction and operation phases for AEC projects. From a technological point of view, BIM can be seen as an evolution from traditional CAD tools to a digital model, based on 3D tools, incorporating variables such as time, cost, sustainability, safety and management, integrating the various stakeholders The final step that combines the most varied technologies present in Construction 4.0, that is the term that aggregates all technologies such as sensors, robotics, RFID, artificial intelligence etc. and defines the future of civil engineering as a whole, but more particularly in asset management, is the concept of Digital Twin(DT). The concept of DT is considered by several authors as the dynamic virtual representation of a physical system that allows a variety of simulations. It is characterized by the ability to synchronize between a virtual system and the physical system itself, by obtaining real-time data from sensors and other smart devices, with the aid of mathematical algorithms, allowing the creation of increasingly accurate virtual models. It is mainly used in the optimisation, monitoring, diagnosis and prognosis of a real system. DT in construction can be considered as the most complete level in virtual conditions with prevention and prediction capabilities to assist in AEC projects, becoming a basic tool in helping to reference the past, control the present and predict the future.(Bolton et al., 2018)(Boje et al., 2020)

The proper management of a group of assets requires effective decision making enabling an organization to obtain the highest profit / lowest loss throughout its entire life cycle. There are studies (Sun et al., 2008)on the type of decisions within an asset management system whereby it is essential not only to understand the type of decision but also its characteristics. Decisions in asset management can also be defined through specific criteria both in relation to their time scale and to the organisational level to which they belong. In terms of their time scale, four types of asset management decisions are acknowledged, and the levels and time interval can be described as a framework in different scales but which are related, as demonstrated in figure 1.

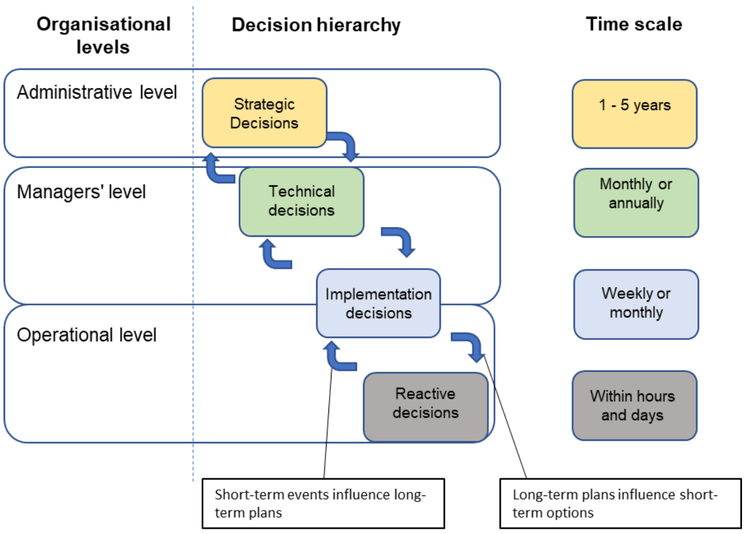

Figure 1 – The correlation between organisational levels, decision hierarchy and their time scale - adapted Sun et al., 2008

The decision-making process in asset management has been taking a central role(Macchi et al., 2018), but this has to be based on a large number of data and information. Currently, with technological breakthroughs, the increase of devices (sensors) that allow the collection of these data has brought several benefits in the decision-making process, since this practice allows to significantly reduce the number of unnecessary maintenance taking into account that it can be based on maintenance actions that are performed at the right time and when they are really needed.

2. MODEL AND CASE STUDY

One of the main objects of research, still under discussion, is the creation of a decision support model, which guarantees the required information to assist the processes within a organization, according to its organizational objectives and intended results. In addition, continuous monitoring is required, which is constantly updated to support changes to input parameters and processes. This chapter aims to present a model for application in the assets of Infraestruturas de Portugal to support decision-making in asset management towards the digital transformation. The formalization, organization and schematization of the organizational context, the input parameters of a process and the decision-making process itself can be based on the CIPO framework (Context, Inputs, Processes and Outcomes)

2.1. DECISION-MAKING FRAMEWORK FOR DIGITAL TRANSFORMATION IN ASSET MANAGEMENT – CIPO METHODOLOGY

The Technical Committee on Asset Management (TC251) is responsible for the development of the ISO 55000 family of standards. These standards aim to define good practices in asset management as well as the requirements for the creation of an asset management system. The CT251 Ad-Hoc Group 3 aims at understanding the guidelines related to the specification, collection, management and analysis of data to support asset management decision making taking into account organizational objectives. Within the key factors mentioned by the group is the guidance for organizations to develop their own decision-making system. It was then proposed the use of the CIPO method (Context, Inputs, Processes and Outcomes). The organisational context and the desired effects (outcomes) are a direct influence on decision making and it should be these that drive the processes and inputs. The CIPO model is considered a decision-oriented model that systematically collects information about a process to identify strengths and limitations in its content or implementation to improve the effectiveness of the process or plan for its future. The focus is on continuous improvement.

As stated earlier the decision-making process can occur at different organizational scale and time phases, it is important to understand that a CIPO model can be implemented in these different situations.

2.2. CASE STUDY – VÁRZEAS BRIDGE

Fatigue is a specific case of degradation which is of great importance in the evaluation of existing steel bridges. Fatigue can be defined as the process of crack initiation and propagation through a structural element due to the action of variable stresses. This phenomenon is of high importance for bridge management because it correlates with the number of stress cycles to which the structure has been subjected. The fatigue analysis system (FAS), for assessing the serviceable fatigue life of a bridge, is a group of interactive and interrelated modules fully integrated with each other so as to provide the expected results. These modules are grouped into three main areas and include technologies relevant to fatigue analysis.

2.3. APPLYING THE FRAMEWORK TO THE CASE STUDY

The CIPO method, as mentioned in chapter 3.1, refers the need to define the organizational context, the inputs, the processes and the outputs

The investment from the European Union has been fundamental to promote a more modern and efficient network, where the focus has been mainly on the rehabilitation and modernization of the infrastructure, enabling an increase in both capacity and speed of the existing networks.

Besides the connection with the EU, the IP group has two contracts with the Government, the general concession contract for the national road network and the programme contract for the management of the national railway network, thus becoming the maximum responsible for infrastructure management.

Also considered within IP's external context are customers, both private and collective users, the regulator that assesses compliance with the contracts referred above, local entities such as municipalities that expect fair and transparent treatment, as well as suppliers where sub-concessionaires, design and construction companies, conservation and maintenance, consultants and utilities suppliers are included.

Decision-making processes, as mentioned above, require a series of input parameters that are defined according to the objectives of the process, i.e. the desired expected results. The FAS modules require a series of data, organised in Table 1. It is this information that will support the processes described next.

Tabela 1 - Inputs of CIPO

Modules	Inputs
General	• Node coordinates, members connectivity, member sections (structural model) • Materials • Detailed information regarding the connections
Dynamic properties	• Modal frequencies of the bridge • Modal damping • Modal vertical displacements of the nodes belonging to the load path • Modal values of the stresses determined considering que mode shape.
Loading module	• Train speeds • Train geometry and loads of each train

Fatigue resistance	• Global
	    • S-N curve
	    • Partial safety coefficients
	• Local
	    • Material S-N curve
	    • local S-N approaches
	    • Stress concentration factor

	• Partial safety coefficients
Inspection/experimental field test	• Dynamic propertites through ambiente vibration tests • Train loading schemes through weight-in-motion systems • Train counting • Characteristics of the materials • Existence of cracks and craks characteristics • Experimentally measured strains for validation of numerical model(real sensors) • Long term monitoring campaigns for in-service load effect estimation
Calculation module	the input from the Database Modules is used to compute the fatigue consumption and an estimate of the remaining fatigue life based on one of the two approaches mentioned in the Fatigue Resistance Module.

The fatigue analysis system is a set of interconnected processes aimed at evaluating the fatigue life of a bridge. Four main processes can be considered within the Fatigue Analysis System, the so-called database process, the inspection and experimental testing process, the calculation process and the fatigue failure process.

The database process considers 4 different modules, the general, the dynamic properties, the applied loads and the fatigue strength. It is the information gathering process that will assist the calculation process. All the inputs mentioned above are included in this process. These inputs are obtained from the organisation's database, numerical bridge models and standards. In order to validate and complete these inputs, the inspection and experimental testing process works in parallel with the database process, validating and completing any information gaps that may exist. The calculation process uses the inputs obtained from the database process and it is in this process that the fatigue consumption and the remaining fatigue life is calculated based on one of the approaches, local or global. Finally, the fatigue failure process includes a decision support module that organises the results of each analysis and makes the appropriate assessments based on the results of the calculations and/or the data from the inspections.

The results of each assessment performed by the system and stored in this process can be used to evaluate the potential for rehabilitation, repair or strengthening operations to extend the service life of the structure. The normative traffic scenarios are intended to simulate traffic to design new bridges and not to study existing ones and so using these extremely conservative scenarios, there are some details that show to be prone to fatigue. However, it should be mentioned that this bridge is situated on a line with low traffic where the tonnage per year is significantly lower than that of the conservative scenarios. In addition, the S-N curve adopted is certainly conservative as is the same curve used for all details.

The main output of this case study is the remaining service life of the Várzeas bridge i.e. 47 years, so it is important to mention that although we talk about decision making process, this output by itself refers the need for intervention, not mentioning the deadline, nor considering other variables, it should in fact be considered a subprocess of decision making.

In the fatigue assessment system, no continuous monitoring system is mentioned because it was a one-time study.

2.4. RESEARCH CONTRIBUTIONS

The case study of the Varzeas bridge, although it is considered a decision-making sub-process, cannot by itself provide a final decision, it can provide a referral decision. The fatigue analysis system that assesses the serviceable fatigue life of a bridge, in the decision-making module organizes the results of the analysis and makes appropriate judgements based on the results of the calculations. However, the final decision to upgrade, maintain or replace the bridge is not made. It is a decision that must be taken into account both at the administrative level, i.e. a strategic decision on a broad time scale, but also at the level of managers, as it depends on technical and implementation issues. In fact, its requalification or replacement not only has very different investment values, which have not yet been considered in the fatigue analysis system, but also has a very large impact on circulation. For a proper decision, a set of monetary factors, constraints, alternatives and environmental impact that have not yet been taken into account is required. The database process presented in the case study is supported by data from the Infraestruturas de Portugal database, more specifically by the inspection reports and pathology survey of the Várzeas bridge carried out in 2018. Subsequently, several visits to the bridge were made to confirm the consistency between the inspection report and the real structure. In fact, it was found that some of the information available in the inspection reports, especially the information relating to the geometric survey, was not in conformity with the real geometry of the bridge, which is why a new geometric survey was requested. Furthermore, due to lack of available information, properties based on available design elements of other bridges, with very similar structural system, built at the same time and designed by the same company, as is the case of Trezói bridge, located close to Várzeas bridge, were used. The lack of accurate data on geometric and material properties leads to relevant inaccuracies in the analysis of this type of structures. The increase and agglomeration of the complexity of the structural issues at stake require the development of accurate numerical models, whose improvement, in the face of the existing uncertainties, can hardly be made based on engineering assumptions, something that is very recurrent nowadays, making the power of argumentation more relevant than the data itself at the moment of decision making. The damage calculated for the residual fatigue life was 47 years, taking into account the normative values, considering heavy traffic, much higher than the real traffic that crossed and crosses and taking into account loads and frequency of train crossings much higher than the one that actually crossed the Várzeas bridge.

The digital transformation in asset management and emerging technologies already mentioned earlier in the document can provide a constant fatigue analysis over time by obtaining data in real time. Starting with obtaining a BIM model in order to characterize the geometry of the bridge as a basis for a reliable assessment in all aspects. In addition to a BIM model, the creation of a GIS model is also essential to characterize the entire bridge surroundings. Emerging technologies such as 3D scanners, in particular LIDAR technology and UAV are essential to capture the geometry of the bridge and, in addition, these technologies aided by artificial intelligence algorithms are able to detect anomalies such as points of particular fragility during the mapping of the structure. These technologies, together with sensors and RFID can obtain the missing data for the analysis of the useful fatigue life of the Várzeas bridge.

Although the current fatigue calculation approaches are widely accepted, it must be stated that the existing gaps in these approaches make their reliability difficult.

For the remaining service life calculation, the digital transformation, and the consequent creation of a DT, uses emerging technology to not only perform the real-time mapping of physical bridges into virtual bridges, which now contains all the information and knowledge, but is also able to perform the diagnosis of fatigue damage so that the prediction of the service life of bridges can be performed efficiently and consequently that decision making is done in a timely manner.

So, on one hand, these models have a highly reliable system of the actual configuration of the bridge with its structural geometry, physical dimensions, material types, both at a macro and micro scale, fatigue defects, manufacturing anomalies etc. On the other hand, the model is capable of accurately simulating physical behaviour of the bridge under the influence of applied loads from a wide variety of sources. More precisely they are capable of simulating the growth of fatigue cracks under the complex interactions of the vehicle-wind-bridge-temperature etc. system during the bridge's service life. AI allows DT to be an autonomous model that continuously updates the digital models and timely returns information that is considered essential for the maintenance of fatigue-related problems, in addition to being able to provide a daily plan of minor corrections to the service that can mitigate fatigue problems, being able in the last case, i.e. in emergency situations, to alert the bridge managers. Considering the various stochastic factors that a bridge may experience during its lifetime, AI significantly reduces the burden on bridge managers. One of the main characteristics of technologies in a DT is the interaction with users. The DT is capable of transforming the information from the assessments made, including those of fatigue, into information that is pertinent to the users. This interface allows users to control and operate the TD in a convenient and efficient way, achieving a bidirectional interaction of a bridge management, with full use of all hardware and software.

Computational power is the central feature of a DT, as it provides much higher computational power than is currently used for fatigue analysis of bridges. The high-speed characteristic of this computational capacity ensures that the fatigue simulation conducted by a DT can be consistent with the actual service of a bridge, i.e. a 1 hour service can be simulated in a real time of 1 hour or less. (Tuegel et al., 2011).

The enormous amount of information and data generated is one of the problems inherent in creating a DT. During the operation and maintenance phase, data from sensors, maintenance reports, simulation history and analysis results etc. are fed into a large database. This is a major problem, as the continuous growth of this structured and unstructured data as well as the diversification of data sources means that traditional procedures such as block or file storage have to be modified. As mentioned before, the case study and the outputs cannot by themselves be the object of decision making.

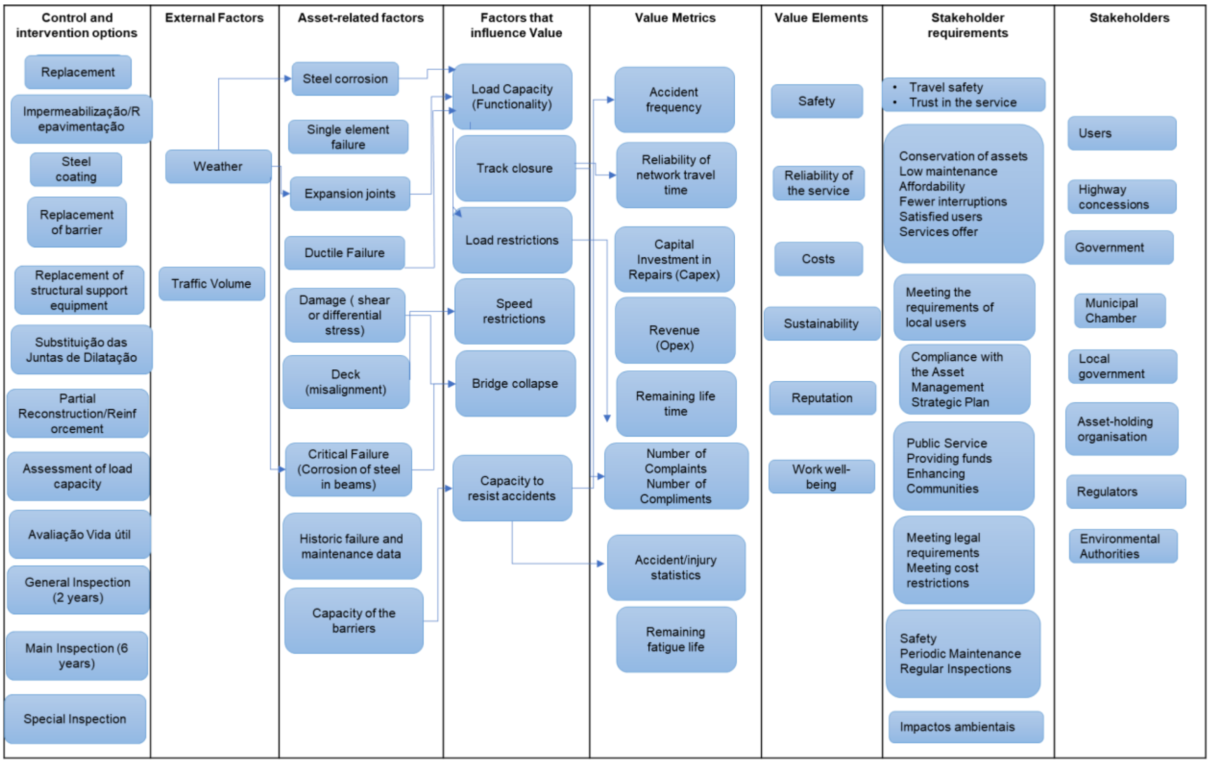

Figure 2 - Factors that influence decision-making on railway and road bridges

Figure 2 shows the various intervention options as well as the various factors influencing decision making in rail and road bridges.

The different factors presented are some of those that are needed for the decision making to be as informed as possible. The set of technologies and solutions presented throughout this dissertation can fill in practically all this necessary information.

The proposal of inserting a CIPO model in a context of digital transformation and implementation of a DT is essential. The proposal refers as a starting point the acquisition of data in real time, where after being explored and together with historical data, they feed processes and models inserted in a DT. Subsequently, the processes and models return the necessary information to support the decisions made by managers. These decisions are added to the historical data and data exploration that are incorporated into new processes and models inserted into a DT, thus evidencing that the decision-making processes within an organization are sequential.

3. RESEARCH LIMITATIONS

One of the objectives of applying the CIPO model, as mentioned by the technical commission for asset management, is to implement a decision-making system that, based on the organisational context, objectives and expected results, defines inputs for decision-making. By applying the model to the case study, it is clear that, as the fatigue analysis system is a very specific case in its objective, it can only refer to something that should be taken into account when making the final decision to repair, upgrade or replace the bridge. Thus, it is only considered a decision sub-process where the CIPO model fulfils its objectives.

Continuous monitoring, as previously highlighted, is not developed in the fatigue analysis system, which is essential for the decision-making process. Although some situations directly related to the implementation of the CIPO model can be solved through the punctual analysis of its operation, some situations will remain unsolved or with a certain degree of uncertainty considering the constant large amount of data that the digital transformation will bring, which will cause the evaluation not to be made within admissible timeframes. Some of the scenarios identified will be more important than others, and there will then a need for prioritization so as not to affect decision-making capacity, and for decision-making to remain as informed and accurate as possible. Both the selection and prioritisation of alternatives to be taken into account and the ability to obtain solutions to them will increasingly depend on an honest exploration of uncertainty and a formal commitment to learning over time. This increasingly means that the post model implementation management regime should be accompanied by an adaptive approach, which includes continuous monitoring. The final step in the decision process is then to identify mechanisms for ongoing monitoring to ensure accountability for results on the field, research to improve the information base for future decisions, and a review mechanism so that new information can be incorporated into future decisions. A rigorous decision-making process for its sustainability is one that will create a history of learning and adaptation, leading to greater capacity in terms of technical information, human resources and organizational capacity to make better decisions in the future. A key challenge will be both to reduce the uncertainties perceived as critical and to create organizational flexibility to respond to new information, without overlapping management and argumentative power over a decision.

4. CONCLUSION

Due to high levels of deterioration, increasing traffic demands, or disused structural design, a considerable part of the existing infrastructure in Portugal presents important challenges regarding its longevity.

The implementation of a proposed traditional decision-making model (CIPO) has shown that it is possible to optimise these processes if it is integrated in a digital transformation environment, for example in the context of the creation of a DT. The context will be obtained by creating the digital models and linking assets of an organisation as well as inputting historical data and organisational goals. The inputs will come from all the technologies mentioned for this purpose, such as UAV's, RFID's and sensors, both fixed in the infrastructures and attached to the vehicles. Processes will be inserted in the computational power inherent to DT, and outputs will be the decisions supported by AI and the improvement in the quality of information transmitted to asset managers in order to support all decisions.

The digital transformation in civil engineering is bringing a significant impact on decision making in infrastructures. Information requirements are essential to the implementation of an effective decision-making system.

It is extremely important in an entity that manages infrastructure assets such as Infraestruturas de

Portugal to create an asset management strategy within the scope of digital transformation. This strategy cannot be supported only by the acquisition of new technologies but supported by a collaboration across the entire organization guided by the objectives set by the administration. This collaboration should consist of the various departments, in order to establish all the information requirements such as financial resources, human resources, engineering, operation and maintenance, technology, etc. The defined strategy should refer to standards that the organization will use to manage its digital assets. These should include nomenclature standards in engineering documents, project delivery, etc. The asset management strategy under digital transformation along with the supporting technology and standards should include audits of the current state of data compared to standards and should determine all missing or suspected inaccurate and incomplete data and information to determine what technologies are needed to fill the identified gaps. This will enable the organization to construct a realistic timetable as required by both financial and human resource requirements. The organization should also consider the cost of collecting missing data versus the value it may bring. There should be an understanding of the risk of not having this data, as it may be preferable to consider old data and ensure standards are in line with this data. The case study analyzed is an example of how it can be preferable to implement the asset management strategy within the digital transformation by stages. Starting with a pilot project, with data collection and goal setting enables the identification of better ways to collect and analyse data and more importantly, will demonstrate the value of having accurate and correct data and information.

With appropriate data and information collected, an infrastructure asset management organization can take full advantage and use tools such as life cycle cost analysis, capital investment planning and risk-based inspections. By having all the information available, organizations can truly assess capital investment plans and justify postponing maintenance or replacement decisions. This provides a new level of transparency and trust between the organization, customers, regulators and stakeholders.

Digital transformation and the implementation of a DT are essential to reach this level of automation of a decision-making process.

5. REFERENCES

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*(January), 103179. https://doi.org/10.1016/j.autcon.2020.103179

Bolton, R. N., McColl-Kennedy, J. R., Cheung, L., Gallan, A., Orsingher, C., Witell, L., & Zaki, M. (2018). Customer experience challenges: bringing together digital, physical and social realms. In *Journal of Service Management* (Vol. 29, Issue 5). https://doi.org/10.1108/JOSM-04-2018-0113

Macchi, M., Roda, I., Negri, E., & Fumagalli, L. (2018). Exploring the role of Digital Twin for Asset Lifecycle Management. *IFAC-PapersOnLine*, *51*(11), 790–795. https://doi.org/10.1016/j.ifacol.2018.08.415

Sun, Y., Fidge, C., & Ma, L. (2008). A generic split process model for asset management decision-making. *Proceedings of the 3rd World Congress on …*, *March*. https://www.researchgate.net/profile/Lin_Ma11/publication/228436164_A_GENERIC_SPLIT_PROCESS_MODEL_FOR_ASSET_MANAGEMENT_DECISION-MAKING/links/0deec533497c636b7e000000.pdf