Silesian University of Technology

DOCTORAL DISSERTATION

in the discipline: Civil Engineering, Geodesy, and Transport

Digital twins of bridges: establishing principles of virtualization with practical use cases

author:

Kamil Korus

supervisor:

Professor Marek Salamak PhD, DSc

additional supervisor:

Jan Winkler PhD

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Gliwice, Poland

Extended abstract

1 Motivations

1.1 Adapt (or shape) to thrive

The world is always changing. This statement – although trivial – is a purpose of digital twinning research. The statement can be expanded. The world is always changing at an increasing pace. This is being validated especially in the last decade with the digital transformation following the concept of Industry 4.0.

Changes divide people into enthusiasts and pessimists, not only for moral and cultural concepts but also for technical innovations. During the Industrial Revolutions, people perceived the coming automation differently: some were excited about more comfortable lives; others were afraid of losing jobs and struggling in the new environment. As we know today, the groups that took the opportunities of technical advances shaped our world.

The ongoing digitization comes with many shifts: reality is being virtualized into a parallel world; people are constantly connected to the web, producing thoroughly analyzed data; artificial intelligence is taking over tasks formerly reserved for humans. The changes bring excitement and fear – both feelings are justified. However – following the maxim “you must develop not to stay in place” – people and industries, whether enthusiasts or pessimists, should be prepared for the changes of the digitization of our lives.

When juxtaposing “bridges” with terms like “artificial intelligence” or “virtual reality”, bridges seem to be a technological relict of ancient times. After all, we are talking about static, monumental structures that, once built, can be left alone to stand for decades. But is it so? Not exactly. Bridges are constantly reacting to varying environmental conditions and forces. The resulting gradual degradation of bridges’ condition can be unnoticed by users but is essential for managers and inspectors. Because of that, bridges must be monitored and maintained. Also, with new materials, structural solutions, building techniques, and complex equipment, bridges are still an area of civil engineering innovations. Nonetheless, the modern world’s conditions push bridges to take the next steps into technical advances. Civil engineering is transforming to adapt to sustainable development goals, ecological aims, and a growing population.

To thrive, one must adapt to changes – especially in technological contexts. But adapting does not indicate a passive and mindless following. It may also mean shaping. In the digital world, industries become interconnected. This cooperation requires new principles and paradigms. Digital twins, a concept perceived as the key component of Industry 4.0, are becoming this multi-industrial paradigm. Digital twinning is already being applied, but its principles are still forming. The principles should be formed not only by programmers or IT engineers but, in the case of bridges, also by the civil engineering community. In that way, civil engineers will contribute to forming the principles of worldwide digitization, and digital twins of bridges will address the needs of designers, engineers, and managers of infrastructure.

1.2 Connectors of people and data

Bridges' impact is visible both in the day-to-day lives of individuals and on the scale of the entire countries and industries, which can be expressed with numbers; the numbers also reveal problems of the existing infrastructure. Only in the USA, there are 619 thousand of bridges, of which 224 thousand require major repair work or replacement [2]. The problem is expanded by its economic scale: the estimated cost of identified repairs is USD 260 billion – a value comparable to the gross domestic product of the Czech Republic (USD 282 billion), New Zealand (USD 250 billion), or Portugal (USD 250 billion).

The number and complexity of bridges increased the importance of managing the growing and also aging infrastructure network. It resulted in bridge management systems and standardization of maintenance, as well as processes of processing facilities' data. These should be adjusted to the novel technical capabilities of digital transformation. However, infrastructure managers still use older practices, despite their flaws: improper data management diminishes efficiency; condition assessment relies on periodic human inspections, displaying risks of omitting defects; aging infrastructure is unproperly maintained, leading to economic losses and posing the danger of catastrophes. The problems of existing infrastructure convince that civil engineering needs the plan to ensure resilience and safety through the entire lifecycle. The plan must consider the specificity of bridges and the requirements of today's world and also benefit from the technical advances.

In the digitized world, bridges evolve from static constructions into services providing multidimensional connection: physical – of communities, and digital – of data. This shift results from the requirements of facilities' managers and the need to ensure the safety and comfort of users. This forces connectivity and integration in the digital dimension, especially in acquiring, processing, and sharing data. Bridges will cooperate with other objects to empower global holistic management and to constitute the digital networks of smart cities. To enable that, we need a multi-industrial paradigm – the world is shifting towards digital twins.

1.3 Aims of the dissertation

The aim of this dissertation is to provide principles for creating and utilizing digital twins of bridges – the virtual counterparts of objects in their whole lifecycle. The proposed concept addresses the general principles of digital twins, the specificity of bridges, and the practices of the civil engineering industry. The practicality of the proposed solutions is upheld with novel use cases utilizing the techniques identified as components of the proposed digital twinning concept.

To reach the general aim of the dissertation, several intermediate aims have been realized.

- Assessment of the current stage of development of digital twins through the study of literature and analysis of the implementations in bridges.
- Identification of the primary techniques to create and utilize digital twins of bridges.
- The proposal of the primary characteristics of digital twins of bridges regarding their lifecycle.

- The implementation of a practical integration of BIM and FEM models in a visual programming environment, aiming to create a partial digital twin in the design phase with the use of an optimization algorithm to automate the design process.
- The implementation of a technique to generate synthetic point clouds, aiming to create and update geometric models of digital twins in the operational phase with machine learning algorithms.

The listed intermediate aims undoubtedly do not fulfill all the general digital twins' requirements defined in the literature. However, digital twins, in the current development stage, are still a forming concept, continually enhanced with new techniques and solutions. The approach presented in the dissertation enables the implementation of digital twins in an evolutionary way. Digital twins do not have to be complete and perfect from the beginning; the concept should mature naturally, alluring practitioners with its benefits. Other important factors are the limitations of time and the scope of the dissertation. The proposed description of the digital twins' characteristics states the primary principles, not the details of technical implementations. Also, the presented techniques for creating and utilizing digital twins are limited to show the potential benefits. Used technologies and solutions regard the selected needs of the phases of design (automation and optimization of the design processes) and maintenance (changes of the facilities' geometries in time). Nonetheless, the use case of generating the synthetic point clouds does not describe the whole process of creation and update of the models with machine learning algorithms but focuses on the first key step to the implementation of such solutions – the acquisition of data. Future work will regard the creation of machine learning algorithms to create and utilize digital twins.

2 Digital twins – the next wave in simulations

Digital twins are virtual counterparts of objects throughout their entire lifecycle. First adopted by NASA [3], today are being implemented cross-industrially, becoming a component of the digital transformation.

A digital twin, as a model coexisting with an object, should be initialized on a design stage, first reflecting the object's idea. With advances in design, it expands into a high-fidelity central data-management system. Then, it is used to plan and optimize production. Utilizing models for simulation and visualization during design and production is already a multi-industrial practice. But digital twinning aims to provide benefits through the entire object's lifecycle. Due to synchronization with the physical counterpart also on the operational stage, a digital twin exceeds the capabilities of isolated models. The virtual and physical counterparts collaborate. Data from the physical object update the virtual system. The virtual system affects the operation of the physical object.

The digital twin collects data to map processes. It registers how the object reacts to different conditions and how the reactions alter over time. Analyses of such big data lead to a better understanding of the object operation. The data also allows training intelligent algorithms to detect patterns and anomalies, evolving the digital twin into a system of growing autonomy in decision-making. The model reflecting the actual state of an element allows extended reliable simulations. Since digital twinning is a cross-sectoral framework, unified data systems allow holistic management, considering relationships of cooperating elements. It leads to global optimizations of economic, ecological, and social costs, keeping the safety of the objects.

Digital twins' interest increases in the academic environment, resulting in a dynamic growth of publications, and in the industry, leading to new implementations. The research is dualistic: both theoretical frameworks and definitions are being established, and practical use cases are being explored. Both aspects have been regarded in this dissertation.

3 The concept of digital twins of bridges

Establishing the foundations for bridge digital twins must start with a vision. But equally important are the enablers for realization. There is no point in forming idealized concepts that are perfect in theory but inapplicable in practice. To develop, digital twinning must be adopted by civil engineering practitioners, so designers, engineers, and facilities' managers. The digital twinning framework should, therefore, rather guide into practical benefits than restrain with idealized rules.

The first civil engineering applications of digital twins utilize modern civil engineering techniques (e.g., BIM, SHM, 3D reconstruction), often blending them and integrating with, e.g., artificial intelligence. The use cases are still partial. They do not implement complete digital twinning but focus on selected functionalities (e.g., isolated semantic models or acquiring SHM data). Nonetheless, the applications promote the automation and digitization of civil engineering, making a ground for digital twins.

This dissertation proposes principles for creating and utilizing the digital twins of bridges (Fig. 1). The proposed concept addresses the general multi-industrial digital twinning fundamentals (identified with the literature study), the specificity of bridges, and the demands of designers, engineers, and managers of civil engineering facilities. The proposed digital twin is a virtual counterpart of the bridge in its entire lifecycle characterized by actuality, intelligence and autonomy, interaction, interoperability, modularity, expansibility and scalability, accessibility and security, and uniqueness. From the technological perspective, it is an evolution of current practices, which have not yet been properly integrated. The proposed digital twin utilizes BIM (Building Information Modeling), SHM (Structural Health Monitoring), and AI (Artificial Intelligence). It states IFC (Industry Foundation Classes) as the base for the central model. It is also enhanced by other techniques (e.g., visual programming, point clouds). This approach enables the evolutionary process of adopting digital twins in civil engineering. Civil engineering digital twinning does not have to be perfect from the start. It should mature naturally, alluring designers, engineers, and managers of civil engineering facilities with its benefits.

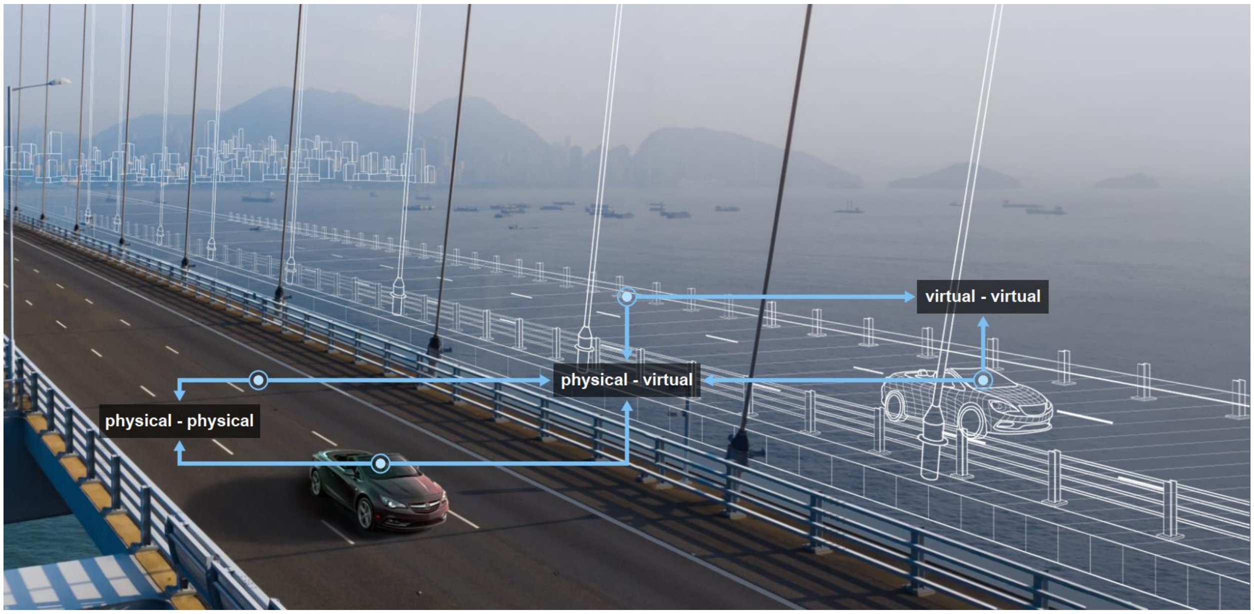


Fig. 1. A bridge digital twin vision

3.2 Techniques of civil engineering digital twinning

This subchapter lists techniques identified as crucial for creating and utilizing digital twins of civil engineering facilities. The listed techniques are:

- Building Information Modeling (BIM),
- Industry Foundation Classes (IFC),
- structural health monitoring (SHM),
- artificial intelligence (AI),
- visual programming (VP),
- point clouds.

The authors describing the implementations of the listed techniques often refer to digital twins. This is understandable, especially given the initial phase of the development of this concept. Nonetheless, calling the implementation of an isolated technique a complete digital twin is not entirely correct. The techniques can be components of civil engineering digital twins, but only their conscious interoperable-oriented mixture enables extensive digital twinning. The BIM model or SHM system is not yet a digital twin. This subchapter describes the differences between these techniques and their use in creating and utilizing digital twins of bridges.

3.3 Notions towards digital twinning of bridges

The dissertation presents notions towards the digital twinning of bridges. The notions complement techniques and characteristics and together can be perceived as an extended definition to guide creating, utilizing, and interpreting digital twins of bridges. The notions (elaborated in this subchapter) are:

- Digital twins allow business thriving in the future;

- Digital twins’ frameworks should be object-specific;
- Ultra-high fidelity is not always required;
- Data synchronization does not need to be perfect;
- Digital twin should not neglect any data freely;
- Digital twin provides data interfaces;
- Digital twin includes processes;
- Digital twin is intelligent, autonomous;
- Digital twin is a system;
- Digital twins widen empirical science;
- Digital twins must provide practical benefits;
- It is the right time to establish digital twinning frameworks.

3.4 Characteristics of digital twins of bridges

The dissertation describes characteristics that complement notions in defining the digital twinning framework for bridges. The characteristics (elaborated in the dissertation) are:

- actual reflection: fidelity and synchronization,
- intelligence and autonomy,
- interaction,
- interoperability,
- modularity,
- expansibility and scalability,
- accessibility and security,
- uniqueness.

The characteristics are interconnected. Actuality, intelligence and autonomy, as well as interaction, are the foundation of the digital twinning concept. Interaction (the ability to cooperate with other objects in the digital dimension) is enabled by interoperability (the compatibility with general principles and standards of data exchange). Modularity enables practical implementations; not all the functionalities of digital twins must be implemented from the very beginning. The expansibility of functionalities and scalability are the results of previous characteristics. Accessibility for users and other instances, but with the security of data, as well as uniqueness (e.g., of identifiers), are the indispensable factors for effective implementations.

3.5 The need for practical use cases

Digital twins, as an emerging concept, still requires extensive research. Stating the object-suited principles is the first step. However, for development, digital twinning must provide practical use cases giving clear benefits to designers, engineers, and managers of facilities.

This dissertation proposes two solutions created by the author, utilizing techniques identified as components of civil engineering digital twinning. The solutions regard various lifecycle phases and provide benefits on the design and operational phases of the objects' lifecycle.

The first proposed solution is the optimization using visual programming and genetic algorithm [183]. Visual programming is used to link BIM modeling, FEM analysis, and optimization algorithm. The solution is a step towards utilizing digital twins' techniques in the design phase. The system is an effective geometrical optimization approach, assisting designers in their day-to-day tasks. Moreover, the integration of BIM and FEM models is crucial for creating a fully-functional digital twin of a bridge.

The second proposed technique is the generation of synthetic point clouds' datasets. Point clouds can be a base for modeling actual geometrical conditions in both operational and building phases. To automate the extraction of point clouds' information or even the generation of geometrical models, often machine learning algorithms are used. However, the available point clouds' datasets are not sufficient for the training of machine learning algorithms. The alternative is synthetic data. A scanning simulator created by the author allows for generating synthetic point clouds from BIM models. Acquiring the data is the first but indispensable step in developing machine learning solutions automating the utilization of point clouds, including systems to monitor geometrical changes in the digital twin models. The scheduled scanning of the physical object and then updating the model with trained algorithms will create a model-based history of geometrical changes. Monitoring, identifying, and comparing the geometrical changes can help identify structural malfunctions. As for bridges, monitoring the geometrical changes is crucial, especially for objects on the ground deformation areas (e.g., mining or post-seismic activities, tunneling). The model updating can therefore lead to expert systems alarming about hazards.

4 Optimization using visual programming and genetic algorithm

The multitude of geometric parameters makes bridges a challenging task for designers. Traditional iterative optimization is time-consuming and usually consists of an insufficient number of analyzed variants, leading to non-optimal solutions. Optimization techniques for bridges are the subject of extensive research. Many of the approaches use text-based programming languages. However, they are not easy to use by non-programmers. The alternative can be visual programming (VL), a more accessible form of developing algorithms. Visual programming is closely linked with BIM environments, where parametricism and quick modifications are essential. Visual programming scripts typically automate parametric geometry modeling but can also serve other engineering tasks. Merged with an optimization algorithm, they constitute an automated design process – generative design. In this approach, a user sets the constraints and ranges of selected parameters, and the algorithm optimally adjusts the values.

A generative design system based on visual programming can perform iterative, computationally-expensive tasks. However, as revealed within the literature study, its utility for bridges is still not sufficiently recognized, especially in the field of finite element analysis; not all civil-engineering visual programming environments provide proper FEM (finite element modeling) analysis tools. And the integration of BIM and FEM models is crucial for creating fully-functional digital twins of civil engineering facilities.

To address this gap, the author proposed [183] a generative design geometry optimization process (Fig. 2) for bridges using Dynamo, an open-source visual programming language popular among civil engineers. BIM and FEM models have been integrated with an optimization algorithm in an automated manner. To enable FEM analysis, Dynamo has been enhanced with a FEM package created by the author. It empowers construction analysis entirely in the visual programming environment, which additionally automates BIM modeling.

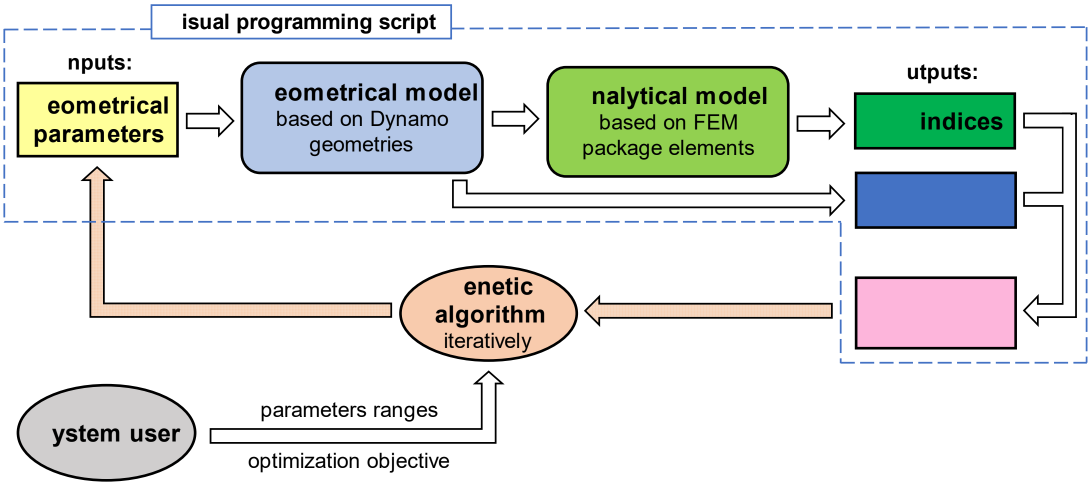
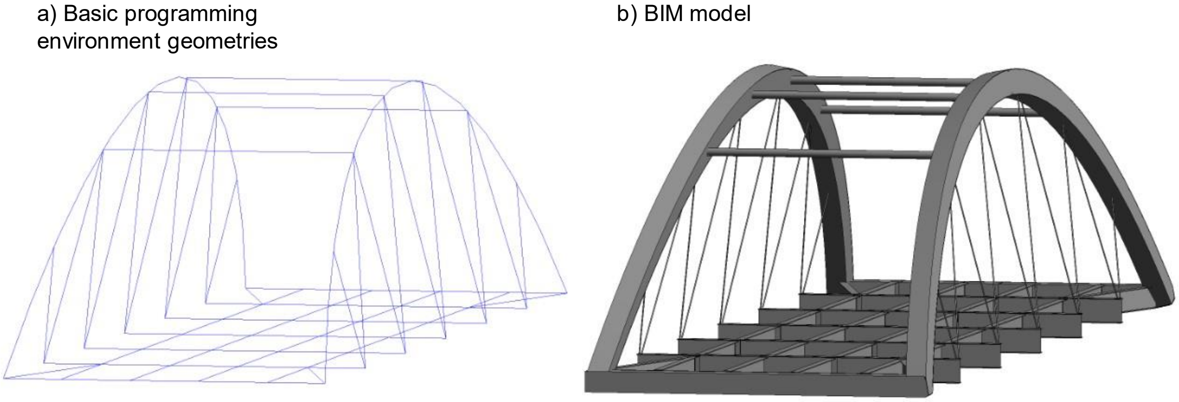


Fig. 2. Generative design optimization system operation flowchart

In a performed experiment, Dynamo scripts generated numerous models as variants of a reference arch bridge. Fig. 3 shows visualizations of basic FEM and BIM models of the bridge. The varying parameters include the hangers' system (vertical, radial, oblique, network), number of elements (e.g., hangers), arch rise, cross-sections' dimensions, and material parameters.


a) Basic programming environment geometries

b) BIM model

Fig. 3. Visualizations of a) basic FEM model geometry and b) generated BIM Model

The generated variants have been analyzed by FEM methods. The linked genetic algorithm took the analysis' results as inputs for the next generation of variants. The algorithm iteratively steered the geometric and material parameters aiming to minimize the objective function. The objective function was relative material cost depending on material volume and its cost factor. The results of the initial analysis are shown in Fig. 4. The initial analysis regarded variants of varying hangers' systems, hangers number, and arch rise. The task was to determine the range of these parameters to be regarded in further analyses. The ranges have been determined by searching for variants of permissible use (Use ≤ 1) and lower relative cost than in the reference structure (MaterialCost < 87,24).

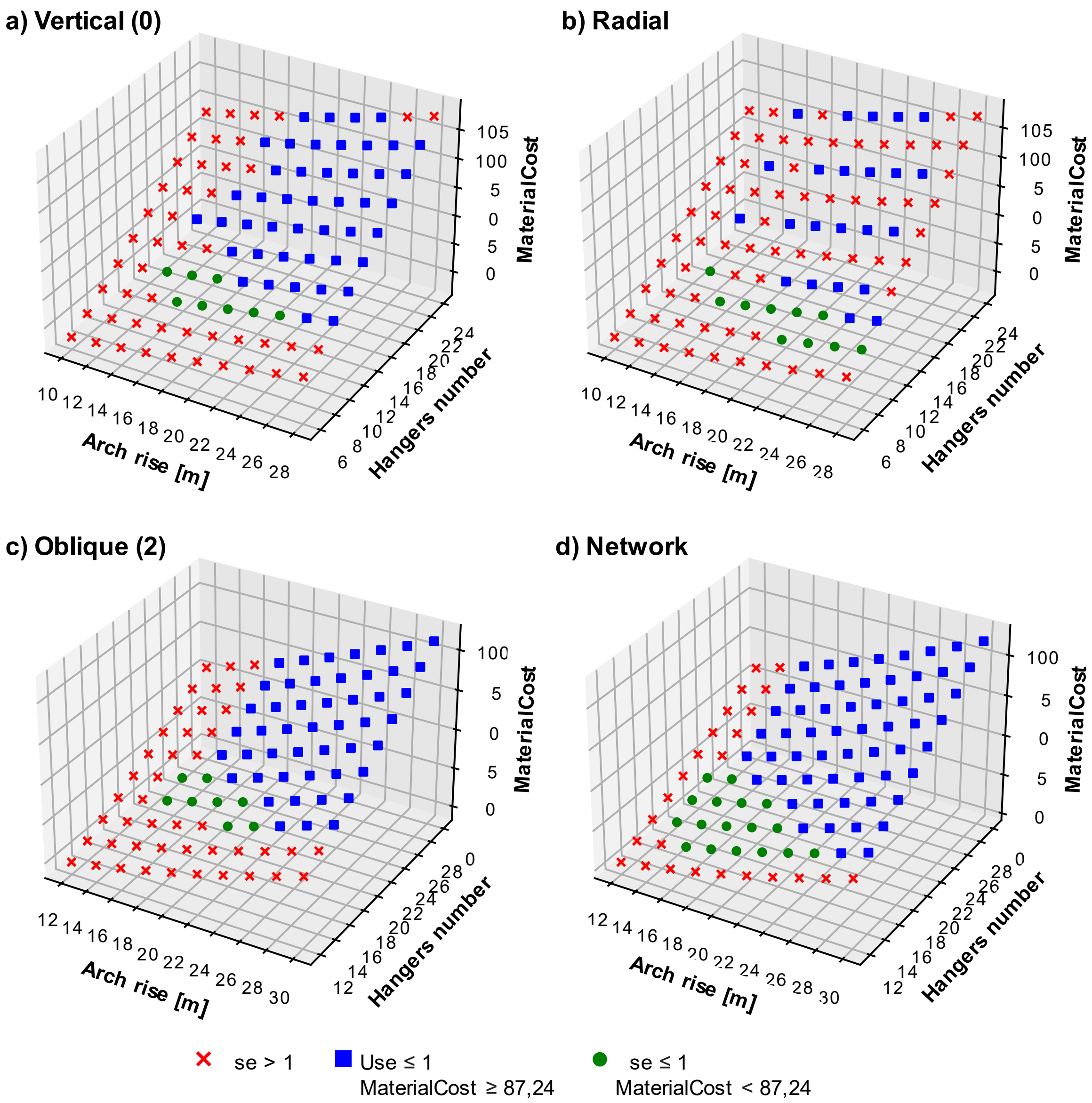


Fig. 4. The initial analysis of the variants of differing parameters' values (hangers' system type, hangers number, and arch rise) with reference to maximum structural use and relative cost

5 Generating synthetic data for point clouds' machine learning automation

Point clouds are becoming basic sources of geometrical data for physical infrastructure. However, data about the construction's shape is insufficient for digitizing facilities in the form of data-rich digital twins and performing advanced analysis – for that, semantic data is also required. Since manual extraction of semantic data from point clouds and its interpretation is time-consuming, error-prone, and inefficient [315–

319], much research effort is put into automation. The automation of point clouds is often based on machine learning (ML).

A properly operating ML system is based on two fundamentals: an algorithm suited for the task and a dataset for training. With the increasing computational power of algorithms, often the data is a bottleneck [244]. A proper dataset should be diverse, reliable, and contain a sufficient number of examples. Also, if the selected algorithm is a supervised one, the data examples must be labeled. If the examples' number is insufficient for the task complexity, ML solutions suffer from the data hunger effect [215] – insufficient training data inhibit achieving optimal algorithms' performance, hindering automation.

The acquisition of point clouds is time-consuming and expensive. Scanning some areas states practical challenges (e.g., closing a road to scan the lower part of a bridge). Moreover, manual labeling of points is tedious. Due to that, large datasets of point clouds are rare. The data hunger problem (the problem of insufficient data) is frequent in point cloud-dedicated ML solutions. One of the methods to overcome the data hunger problem is producing synthetic data. Synthetic data have some advantages compared to real data. Primarily, it is easier to acquire since there is no need for numerous scanning. Synthetic data is also scalable (the amount of generated data is limited only by computation power) and gives control over examples' features and distribution. Moreover, synthetic data ensures reliable annotations. However, to be used as an enhancement or replacement of real data in the process of training the machine learning algorithm, synthetic data properties should mimic the properties of real data.

Synthetic point clouds can be generated by geometrical models' sampling or by scanners' simulators. These techniques allow for preparing synthetic machine learning datasets acting as enhancements or replacements of real data. Several attempts have been made to create simulating tools [331,332,334–336,338,340,342,343]. However, there is still a lack of publicly available solutions that give sufficient control over simulation parameters and acquired point clouds' properties, emulate the operation of scanners, and do not require dedicated preparatory work (e.g., creating models only for the scanning simulation).

The author decided to address the need to generate synthetic point clouds. For this purpose, the author developed a simulator of laser scanning called DynamoPCSim. The simulator generates synthetic point clouds from geometrical and BIM models. Fig. 5 shows examples of the generated synthetic point clouds. The examples present a column of a bridge on which in-situ experiments have been performed. The simulator is based on ray tracing, a technique matching the operation of scanning lasers. Due to that, the produced point clouds' characteristics are closer to the real ones. The simulator is deployed as an add-in (a package) to Dynamo, an open-source visual programming environment. Since Dynamo enables linkage with Autodesk Revit modeling software, the simulator can utilize BIM models directly without requiring dedicated models prepared only for the purpose of scanning simulation. Due to the modular structure of the simulator and the flexibility of visual programming, it can be adjusted to different scanning properties and point clouds' parameters to be acquired.

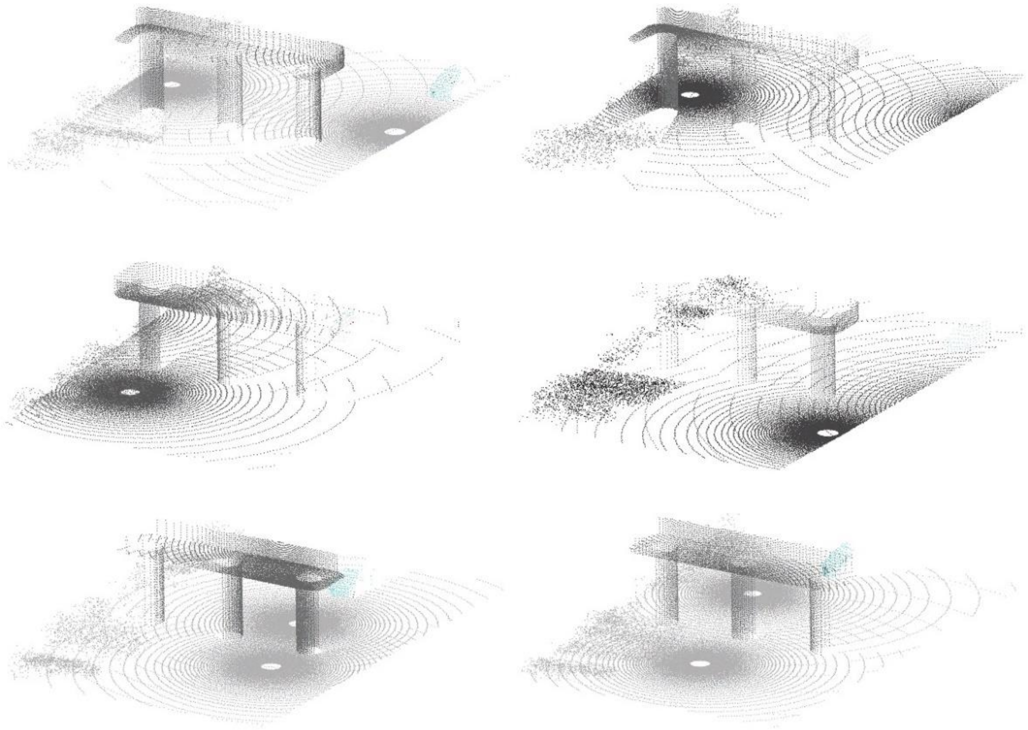
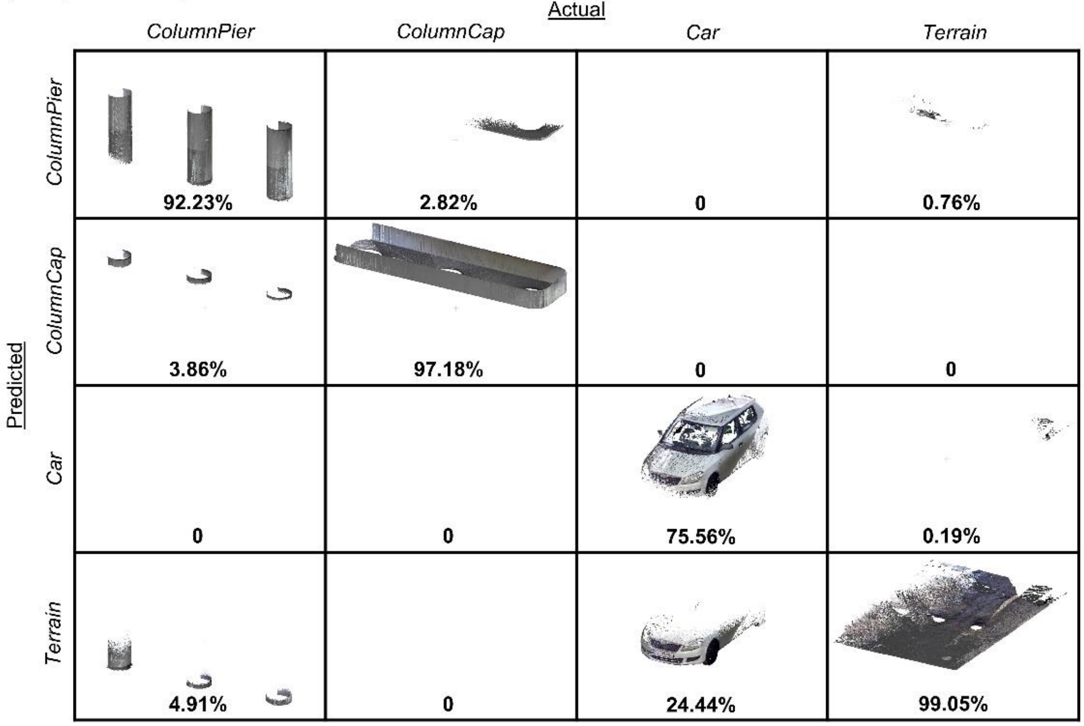


Fig. 5. Examples of synthetic point clouds generated with DynamoPCSim

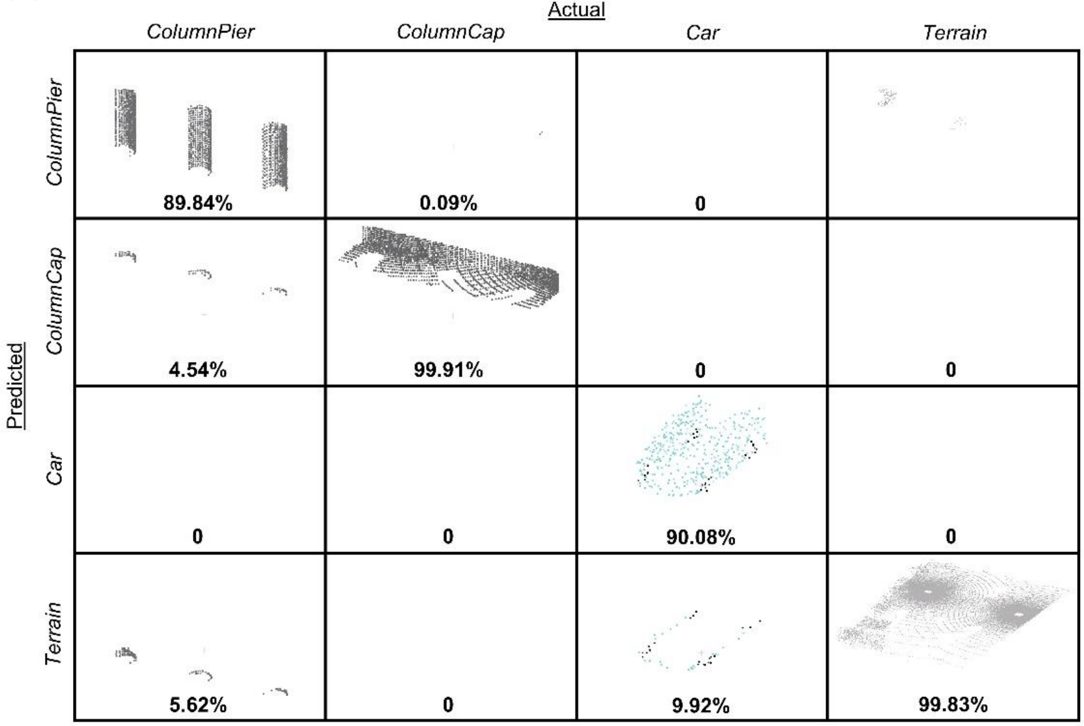
A performed in the chapter experiment of semantic segmentation using a neural network confirmed the usability of generated synthetic data for machine learning. In the experiment, the PointNet neural network [222] was trained on synthetic point clouds. Then, it was validated on test sets. The first test set contained scenes of a synthetic point cloud, and the second – scenes of a real one. Fig. 6 shows confusion matrices of the predictions on both sets. The results are comparable in the recall metric. It indicates that generating synthetic point clouds can replace acquiring real point clouds in the training of a neural network.

a) real point cloud's predictions confusion matrix



Predicted \ Actual	ColumnPier	ColumnCap	Car	Terrain
ColumnPier	92.23%	2.82%	0	0.76%
ColumnCap	3.86%	97.18%	0	0
Car	0	0	75.56%	0.19%
Terrain	4.91%	0	24.44%	99.05%

b) synthetic point cloud's predictions confusion matrix



Predicted \ Actual	ColumnPier	ColumnCap	Car	Terrain
ColumnPier	89.84%	0.09%	0	
ColumnCap	4.54%	99.91%	0	0
Car	0	0	90.08%	0
Terrain	5.62%	0	9.92%	99.83%

Fig. 6. Confusion matrices (with graphical outcomes) of neural network's operation on a) the real point cloud and b) a synthetic point cloud

The created by the author simulator addresses the first but indispensable step in developing machine learning solutions automating the utilization of point clouds – acquiring the data to train the algorithms. The trained systems can extract point clouds' information, segment them, and finally, also generate and update the point-cloud-based geometrical models of digital twins. The automatically updated models will match the real conditions of the physical objects, realizing the idea of a model coexisting with an object through the whole lifecycle, also in the operational phase. As for bridges, the information about geometrical changes will allow to detect and compare deformations, monitor the structure, and alarm about hazards.

6 Conclusions

The ongoing digital transformation is undoubtedly a challenge – but also an opportunity. Given the increasingly complex interconnections of scientific and industrial activities of various sectors, digital twinning improves the effectiveness of civil engineering and enables interdisciplinary cooperation. It also delivers new, practical tools, assisting designers, engineers, and managers in day-to-day tasks.

The proposed in this dissertation idea of a digital twin of a bridge is one of the first approaches to establish the foundations for these data-rich models of bridges. The dissertation identifies techniques for creating and utilizing digital twins of bridges and proposes their characteristics. The proposed concept addresses the general multi-industrial digital twinning fundamentals (identified with the literature study), the specificity of bridges, and the demands of designers, engineers, and managers of civil engineering facilities. With this approach, a digital twin of a bridge is ready for digital cooperation with other instances but also already delivers practical benefits. The benefits are, among others, the automation of the design, assessment of the structural condition, and effective data management. These benefits are realized by new digital twins' use cases. Two of these approaches have been proposed in the dissertation.

The first proposed technique is the automation of design using visual programming and genetic algorithm [183]. The solution presents how visual programming can integrate BIM and FEM Models. Such integration is crucial for creating fully-functional digital twins of bridges. Moreover, the implemented optimization algorithm allowed for analyzing much more variants than in the traditional design. It leads to optimal structural choices and enhances the effectiveness of the process.

The second proposed solution regards creating and updating geometries of digital twins also in the building and operational phases. It is a technique to generate synthetic point clouds as datasets to train machine learning algorithms. The trained systems can extract point clouds' information, segment them, and finally, also generate and update the point-cloud-based geometrical models of digital twins. The automatically updated models will match the real conditions of the physical objects, realizing the idea of a model coexisting with an object through the whole lifecycle, also in the operational phase. As for bridges, the information about geometrical changes will allow to detect and compare deformations, monitor the structure, and alarm about hazards.

The aspects regarded in the dissertation represent the initial stage of research on digital twins of bridges and should be further developed. The directions of further work concern both the theoretical foundations defining these virtual objects and practical ways of utilizing them. First of all, the technical implementation details of the proposed digital twins' characteristics should be determined. In the future, the concept will also need to comprise new, emerging technologies. As for the automation of the design using visual programming and optimization algorithms, additional aims should be considered. Today, mainly economic costs are taken into account. Nonetheless, environmental and social costs have already started to gain significance. And analyses of these parameters are enabled in BIM environments.

As for generating synthetic point clouds, the proposed technique is only the first step in the creation of digital twins in the operational phase. In further work, the synthetic data should be used to train machine learning systems that generate and update geometric models of digital twins. This will open up the possibility of creating expert systems for detecting geometric changes and alarming about potential dangers.

The conducted analysis of the state-of-the-art of digital twins of bridges, conceptual work, and in-situ experiments allowed for achieving the aims stated at the beginning of the dissertation. The foundations for the creation of digital twins of bridges have been declared by proposing a framework that takes into account the specificity of bridges and their lifecycle. It allows for the virtualization of not only physical objects but also their accompanying processes. The author is aware that the presented material does not fulfill all the assumptions of the digital twins' concept. However, the presented research and the resulting acquired competencies are the catalysts for further activities that will aim at increasingly complete implementations of digital twins of bridges in the future.