CHAPTER 3

Reengineering of management processes for the restoration of transport and logistics infrastructure through image recognition and BIM-oriented remediation

Tetiana Cherniavska
Bohdan Cherniavskyi
Oksana Zghurska
Serhii Kasian
Kateryna Nakonechna
Yaroslava Mudra

Abstract

In the context of eliminating the consequences of emergency events (military conflicts, natural disasters, man-made accidents, etc.), it is appropriate to focus attention on issues of reengineering of infrastructure facilities, since the tasks go beyond traditional engineering design and include redesign of the managerial contour of the transport and logistics system (S&D → BIM/DT → 4D/5D → BPMN), re-assembly of roles and responsibility, implementation of end-to-end traceability (CDE/DT), risk-oriented prioritization and audit-ready frameworks of quality, safety and ecology. The authors of the monograph expanded the theoretical framework of the semantic content of the concept "reengineering" in the context of BIM/Digital Twin-oriented reconfiguration of the architecture and processes of remediation/reconstruction/restoration of transport and logistics infrastructure facilities on the basis of observation and diagnostics data. The increase in the scale and diversity of risks of a different nature determines the need to move from static regulations to a data-driven approach, namely: expanding the range of application of computer vision, analysis of images and UAV imagery, satellites, as well as neural-network recognition, which can be organically integrated with the BIM model of the facility, thereby forming a "digital twin". Such coupling will make it possible to provide a full cycle screening → diagnosis → prognosis → intervention, which will make it possible to automatically identify defects, verify their spatial-semantic localization in BIM, assess the degree of risk of collapse of the facility and/or failure, and on the basis of this – predict the operational life of structural elements. All this

DOI: 10.21303/978-9908-845-05-0.ch3

will make it possible to carry out more accurate planning of remediation/reconstruction/restoration works (4D/5D), choose the optimal scenario and protocol of necessary measures, effectively manage the course of implementation of the complex of works for restoration with subsequent successful commissioning of the facility into operation and audit. The authors of the monograph substantiated that BIM technologies play the role of a driver in BPR (business process reengineering) of the transport safety management system as a whole, since they are able to combine surveillance and management of restoration and repair works within operational requirements in a single information contour, while increasing the speed, accuracy, safety and minimization of risks of different nature and scale. The study proposes a metric support, which will make it possible to assess the effect of the implemented complex of works. Thus, the result of reengineering is proposed to be assessed using an integral indicator BOR-Index, which includes an assessment of safety, time, cost, quality, DT-fidelity, completeness of evidence, timeliness, and the readiness of data and processes to be assessed using the I-Score index by levels of interoperability (syntax/formats, semantics, process, operational, evidence/CDE). The monograph studied and proposed a transferable benchmark of construction and restoration of the Genoa bridge (Italy) as confirmation of the feasibility of the coupling S&D → BIM/DT → 4D/5D in fast-track mode.

Keywords

BIM, Digital Twin, BIM-oriented remediation, restoration, transport safety, transport, logistics, infrastructure facility, interoperability, 4D/5D management, BPMN orchestration.

3.1 Introduction

First of all, attention should be focused on the relevance and significance of this problem area, which is determined by a number of facts, namely:

– the growth of the frequency and severity of emergency events, including military conflicts, which lead to large-scale damage to infrastructure, including transport and logistics infrastructure facilities, which directly affects the level of national security and carries the risk of economic losses;

– the limitations of the traditional approaches used for eliminating the consequences of emergency events and for the operational restoration of the transport and logistics system;

– the emergence of an innovative technological "window of opportunity", which is determined, first of all, by the scaling of the use of sensors, unmanned aerial vehicles (drones), satellite data, edge-AI, as well as the maturity of BIM/IFC, and the introduction into the practice of carrying out repair and construction works of 4D/5D;

– the presence of a significant scientific-and-practical gap, which consists in the shift of the focus of scholars to the problems of defect detection of the functioning of transport and logistics infrastructure facilities and the not fully researched issues of using the potential of BIM/DT in the context of selecting optimal managerial decisions and quality control of remediation, reconstruction and restoration measures [1].

The authors of the study examined benchmarks of effective application of BIM, in particular, projects on eliminating the consequences of events of a military nature in Iraq [2] and the project of construction and restoration of an infrastructure facility in Italy [3], which updates the problem area of expanding the range of application of BIM/Digital Twin technologies in the transport and logistics sphere.

The authors defined the aim of the study – to form a holistic methodology and management architecture for the reengineering of affected transport and logistics infrastructure facilities based on end-to-end integration S&D → BIM/Digital Twin → 4D/5D+BPMN within the framework of ensuring transport safety, with a formally verifiable effect by the integral indicator BOR-Index, assessing safety, time, cost, quality, DT-fidelity, evidence, timeliness of the implemented complex of works and the interoperability profile I-Score [4, 5].

In the course of achieving the set goal, the authors performed the following tasks: substantiate the theoretical foundations of BIM-oriented remediation in the context of Surveillance & Diagnostics; form a conceptual model "surveillance → diagnostics → prognosis → intervention" in order to ensure operational management of transport safety; analyze the role and significance of the 4D/5D approach and at the same time to define the role of BIM as the "sense organ" of the digital twin; develop and propose an integration architecture and principles of interoperability; study the possibilities of transferring benchmarks of remediation/reconstruction/restoration of transport and logistics infrastructure facilities into projects for eliminating the consequences of emergency events.

3.2 The theoretical foundations of BIM-oriented remediation of transport infrastructure facilities

First of all, within the theoretical basis, it is necessary to define the key concepts and boundaries. The scientific reconnaissance of published sources on this topic carried out by the authors revealed that most works focus on detection [6]. However, in the authors' opinion, CV/ML can initiate the actions undertaken inside BIM/DT –

from a defect map to a work schedule and budgets. In such a case, it is necessary to substantiate semantically and describe the geo-referencing of the recognized object (in this case, an element of point and/or linear infrastructure). This concerns the transfer of a pixel mask/box into the object-oriented structure of BIM (for example, a bridge element, a road-surface layer, a section of railway track, etc.), which is critically important in the context of remediation, reconstruction and restoration as a result of repair-and-restoration works after emergency situations or military conflicts, but is rarely described as a logical bridge between AI and engineering practice [7].

The ideational impulse for searching for solutions to the tasks set in this study was a medical analogy. Namely, let's rely on the medical chain of continuity of care delivery → screening → diagnosis → prognosis → intervention → rehabilitation: screening as early identification of the condition, the clinical pathway through establishing a diagnosis and forecasting risk, and then therapeutic intervention and subsequent rehabilitation aimed at restoring functions and reducing disability. This intuitive sequence is used to clarify the logic of the engineering-and-managerial picture in the context of post-war and post-disaster restoration of transport and logistics infrastructure [8].

According to the authors' vision of the monographic study, architectural-and-process reengineering constitutes a purposeful, standards- and metrics-based transformation of data architecture, roles and services, as well as end-to-end managerial processes of the national (including regional) system for ensuring transport safety and its remediation in the process of eliminating the consequences of emergency events [9, 10]. This transformation covers the contour: "surveillance → image recognition → situation assessment → action planning → risk assessment → implementation of a complex of works on remediation, reconstruction and construction → commissioning of facilities into operation → post-monitoring" through integration of:

– Surveillance & Diagnostics (S&D), which includes computer vision/ML, UAVs, satellites (optical/SAR), (ground/airborne) LiDAR, IoT;

– BIM/Digital Twin (DT) as a semantic core (in accordance with IFC/BCF, ISO 19650), in which the states are fixed as-designed → as-built → as-damaged → as-repaired/as-remediated;

– the operational layer, which, among other things, includes BPMN orchestration, 4D/5D planning, as well as quality control, occupational safety, environmental control and audit.

Reengineering of the transport safety assurance system within the aggregate of all structural elements of the territorial transport and logistics system covers the entire multi-level ecosystem of participants (including public administrative bodies, operators, contractors, transport and communications regulators, financial donors, etc.), all classes of transport and logistics infrastructure facilities (linear and point), the life cycle of remediation/reconstruction/restoration works, as well as the security and interoperability policy [11].

In the authors' conviction, the term "reengineering" most accurately describes the initial need to restore the functional properties of the transport and logistics system in the event of emergency situations, namely: destruction of a facility (complete or partial), disabling of infrastructure facilities and its unfitness for further operation, as well as complete and/or partial impossibility of carrying out the main processes for safety reasons. As a result of this, the relevant governing bodies face, determined by these circumstances, a goal – to radically redesign the architecture of data, roles, processes and decisions (S&D ↔ BIM/DT ↔ BPMN + 4D/5D) taking into account risks, standards and regulations, technical, technological, as well as financial capabilities (**Fig. 3.1**).

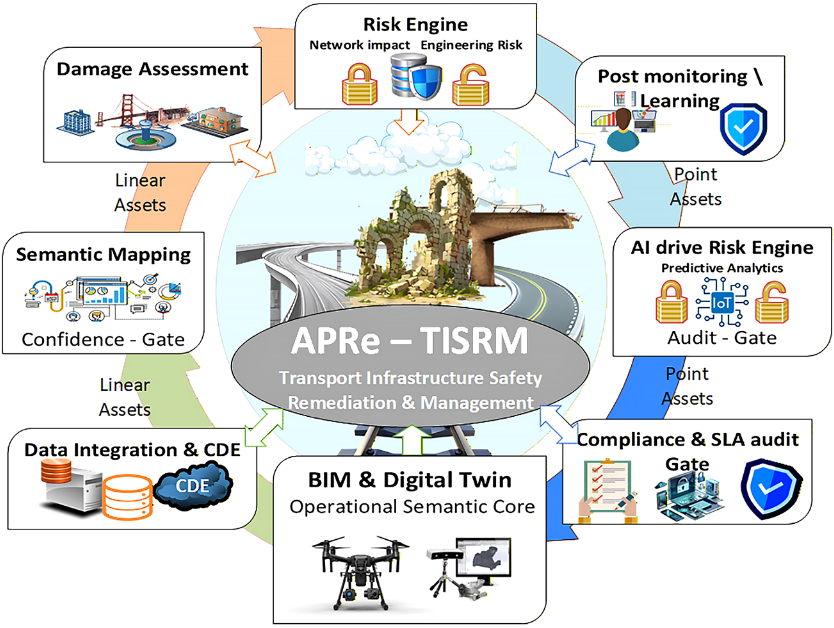


Fig. 3.1 Structure of APRe-TISRM (architectural-process reengineering for transport infrastructure safety, remediation & management/restoration)

Summarizing everything above, it is possible to state that BIM and Digital Twin form a single axis, where BIM acts as a semantic foundation (IFC/BCF), which makes it possible to structure the geometry, composition and hierarchy of all infrastructure elements, the typology of defects and the necessary restoration-and-repair, as well as remediation/reconstruction/restoration works, also for the purposes of resource justification. Digital Twin acts as an operational "living" mirror above BIM, which makes it possible to synchronize the model with actual observations [12], as well as to record the states as-designed → as-built → as-damaged → as-repaired/as-remediated, implement scenarios and, while closing control loops, implement the function of a semantic container and a "sense organ" that is capable of integrating observation streams. In turn, Surveillance & Diagnostics is interpreted by the authors as a triad of interrelated functions: surveillance through the collection and processing of data of transport and logistics infrastructure facilities, recognition of patterns, and on this basis – diagnostics and prognosis with the corresponding engineering conclusions and managerial decision-making.

Surveillance & Diagnostics (S&D) act as a kind of "sense organ" of the system, which makes it possible to carry out comprehensive multimodal surveillance through the integration of the received information of video surveillance, UAVs, satellites, LiDAR, as well as IoT, etc. [13]. Then, identification and verification of patterns is implemented: the results of diagnostics and prognoses are semantically addressed to BIM elements or chainage segments (with an indication of the degree of confidence and the level of error).

According to the authors' view of the study, the uniqueness of BIM technologies lies in the fact that they directly influence critically important factors in the remediation/reconstruction/restoration of transport and logistics infrastructure facilities, namely, 4D (time) and 5D (cost) in operational management, scenario planning of the protocol of necessary works, resource optimization, risk reduction and ensuring safety [14]. 4D and 5D are layered onto the semantic model of organizing the implementation of a complex of measures that are multidirectional by nature, which makes it possible to implement optimal scenarios for restoring an infrastructure facility, while taking into account access possibilities, time windows, weather and technical-and-technological conditions, as well as the possibility of implementing combined measures. In turn, BPMN orchestration makes it possible to take into account and to highlight priorities in restoration scenarios into executable processes with human (Human-in-the-Loop) and automated multi-agent (AOAM) participation where required [15, 16].

Thus, in APRe-TISRM, BIM/DT acts simultaneously as a semantic container and an operational platform, which makes it possible to translate recognition results into manageable decisions, which as a result can significantly accelerate the remediation/reconstruction/restoration of facilities (4D), optimize the budget (5D), and at the same time ensure environmental and transport safety as a whole (including, through aggregating a database of quality control of performed works, compliance with standards and norms, etc.).

The next theoretically significant aspect is that, in the context of post-war and/or post-disaster recovery, the concept of remediation should be considered at least in terms of three interrelated layers [17], namely:

– *technical remediation (engineering remediation)*, which covers a set of measures to restore the main functional characteristics, eliminate defects and vulnerabilities, bring facilities to safety and reliability operation standards, and in some cases – redesign of transport and logistics hubs;

– *environmental remediation*, including, among other things, decontamination, extraction, sanitary-and-environmental control, returning the facility to economic use and preventing re-contamination;

– *socio-economic remediation*, namely, restoring accessibility and connectivity of the entire transport and logistics system, reducing the time of logistics costs, restoring network load, commodity flows, activating population mobility and employment, active use of services by all subjects of the system – that which in the logic of Build Back Better means not simply "return it as it was", but optimize the operational resource and increase the resilience of point and linear infrastructure facilities.

In accordance with what is indicated above, in APRe-TISRM this is reflected through the implementation of a complex of multidirectional remediation/reconstruction/restoration measures, covering a set of technical + environmental + socio-economic interventions, stitched through BIM/DT, making it possible to fix the semantics of the state of facilities, S&D (surveillance → recognition → diagnostics), 4D/5D scenario planning and BPMN orchestration with built-in Eco/Safety/Audit gates, as well as the corresponding KPIs.

Summarizing everything set out above, it is possible to state that BIM-oriented remediation is an integrated (technical, environmental and socio-economic) set of multidirectional interventions managed through BIM/Digital Twin, which play the role of a semantic-and-operational core, where S&D events are addressed to IFC elements and chainage segments, translated into 4D/5D scenarios with Eco/Safety gates, and the implementation is fixed as as-remediated in the CDE with an audit of the performed actions and calculated effects.

3.3 The methodological framework for managing remediation/reconstruction/restoration of affected transport and logistics infrastructure facilities

The process-and-architecture model APRe-TISRM substantiated in the previous chapter covers the end-to-end managerial contour of all remediation, repair-and-restoration and construction measures for transport and logistics infrastructure facilities: from identification and verification of damage – to diagnostics of the possibility of putting into operation after carrying out the required protocol of works with account of prioritization, then to 4D/5D scenario planning in linkage to process orchestration of the set of measures, and at the final stage – to commissioning of the facility into operation on the basis of the conclusion of a comprehensive independent audit with subsequent post-restoration monitoring (with possible model training).

It should be especially emphasized that the semantic foundation of the framework sets the axis S&D → BIM → Digital Twin → BPMN + 4D/5D. In it, S&D (Surveillance & Diagnostics) plays the role of the "sense organ" of the system, where multimodal data sources, including information from video surveillance cameras, UAVs, satellites, LiDAR, etc., through fusion and registration are transformed into detections/masks/anomalies with an assessment of the degree of confidence. Aggregated S&D detections after fusion undergo geo-referencing and are addressed to the corresponding IFC elements for point infrastructure facilities and to chainage segments for linear infrastructure facilities with records of the degree of confidence and errors. All this is stored in the DT state and influences the Confidence-Gate/HIL.

BIM occupies a central place in this foundation; in it, data about a specific infrastructure facility are collected step by step and then, if necessary, used, starting from the design stage and ending with its demolition (including key technical characteristics, dimensions, cost, data on changes made during operation, etc.). Digital Twin serves as a kind of operational mirror, which makes it possible to synchronize the actual states of the facility (as-designed → as-built → as-damaged → as-repaired/as-remediated) and link the surveillance carried out during restoration with the chosen strategy, tactics, the established protocol, plans and deadlines of works. On this foundation, a risk engine of managerial decisions operates, which forms the prioritization of interventions and the choice of optimal scenarios of remediation/reconstruction/restoration of infrastructure facilities based on engineering risk, environmental and socio-economic risks, as well as the overall impact on transport safety.

The actual implementation of the functions of the framework described above is ensured by 4D/5D planning and BPMN orchestration. As indicated earlier, time (4D) and cost (5D) are layered onto the semantics of BIM in order to be able to form a set of permissible scenarios of remediation/reconstruction/restoration of facilities and choose from all permissible ones the optimal one, taking into account access windows, the level of safety of carrying out the protocol of measures, actually available resources and supply capabilities, as well as taking into account routing of construction-and-repair crews for linear infrastructure facilities and staging of performed works for point facilities. The described processes can be presented as a chain of interrelated actions Intake → Verify (HIL) → Triage (risk) → → Plan (4D/5D) → Execute → QA/Accept → Monitor, where Human-in-the-Loop is engaged at a low degree of confidence of image recognition and in the case of critical extraordinary situations.

In the described configuration, the mechanism of manageability is regulated by "gates", namely: a Confidence-Gate for the purpose of verification of the segregation of S&D events with a low degree of confidence; an Eco-Gate in situations where carrying out a complex of remediation measures is mandatory from the standpoint of ensuring environmental safety (including remediation of the infrastructure facility itself, the territory on which it is located, as well as air and water) in cases of exceeding standards and regulations; a Safety-Gate in the case of the need to ensure access for carrying out the required protocol of works (including the need for demining, equalization the impact of weather conditions that hinder/make impossible the implementation of remediation/reconstruction/restoration operations, as well as taking into account actual technological windows); and at the final stage an Audit-Gate, which makes it possible to put the facility into operation only if there are artifacts as-repaired & as-remediated. All the above-mentioned artifacts, scenarios and protocols are maintained in the CDE based on the standards ISO 19650, IFC/BCF, BSDD, OGC/INSPIRE, which ensures interoperability, ensures automated interaction between heterogeneous systems without limitations, which makes it possible to carry out technical, donor financial and ESG audit.

It should be noted that, at the same time, the framework described above makes it possible to clearly distinguish two classes of infrastructure facilities – linear (including: highways, railways, tunnels, metro lines, etc.) and point (including: bridges, transport hubs, seaports, railway stations, airports, etc.). Each of them has different data addressing (chainage vs. IFC hierarchy), different profiled metrics, as well as different planning models and protocols for carrying out remediation/reconstruction/restoration works. It is important to note that this separation is embedded at all levels – from S&D mapping to KPI.

As was substantiated earlier in the study, in APRe-TISRM remediation is understood by the authors in an integrated manner, namely, as a set of various technical, environmental and socio-economic interventions in the logic of Build Back Better, in which the goal is not only to return the functional qualities of the facility, but also to optimize operational properties, increase its level of resilience, transport safety, and also increase the efficiency of the transport and logistics network as a whole. For these purposes, it is appropriate to implement in the framework a system of SLA/KPI management tools with the possibility of exporting them in open formats.

Thus, APRe-TISRM is not only a set of technologies, but also an executable methodology that makes it possible to transform the system of continuous monitoring of point and linear transport and logistics infrastructure facilities into a manageable system of their optimal operation based on the key parameters of ensuring transport safety, thanks to data standardization, process discipline and clearly defined responsibility.

Table 3.1 presented below serves as a bridge between the methodological description and the logic of the framework's functioning. It records those very "joints" of the data → decisions → actions → evidence contour, starting from the mapping of S&D events, including IFC elements and chainage segments – through updating the states of facilities in the Digital Twin – to launching the risk engine for managerial decision-making with the selection of strategy, tactics, priorities, optimal protocols and scenarios with subsequent 4D/5D planning, and then to process orchestration and completion of remediation/reconstruction/restoration works with an evidence base of compliance with norms and standards in the CDE.

Table 3.1 Method for calculating BIM/Digital Twin indicators in the APRe-TISRM framework

Indicators	Role in APRe-TISRM	Key variables	Formula/rule
1	2	3	4
Mapping of Pixel/Track objects → → IFC/Chainage	Transformation of S&D events into manageable data (IFC GUID/chainage segment)	$d \in D$ – an S&D event (detection/anomaly/ change) obtained from surveillance sources; A; $u(d)$ – degree of confidence; $\varepsilon(d)$ – registration error	$f: D \to A$, where A is the set of infrastructure addresses: IFC elements (point assets) and chainage segments (linear assets); $f(d) = \mathrm{argmax}\_\{a \in A\}\ \mathrm{Overlap}\_\{geo/sem\}\ (d, a)$; $u(d)$ and $\varepsilon(d)$ are stored in the DT
Confidence-Gate	Filter for inaccurate data, as well as data with a low degree of confidence; $u(d)$ – confidence for event d [0…1]	$u(d)$ – confidence for event d [0…1]; $\varepsilon(d)$ – geo-registration error of event d (m/pixel/ arc sec); θ_c, θ_ε – thresholds for the Confidence-Gate (minimum acceptable confidence and maximum acceptable error)	If $u(d) < \theta\_c$ or $\varepsilon(d) > \theta\_\varepsilon \Rightarrow$ HIL/inspection, prohibition of auto-generation of tasks until verification
Facility state → DT	Life cycle and history of a structural element of an infrastructure facility (versions in the CDE)	$x_i(t)$ – the state of DT element i over time (parameters of the detected defect, load/environmental indicators, statuses)	$x_i(t^+) = \mathrm{Update}(x_i(t), f(d), \mathrm{evidence})$; states: as-designed → as-built → as-damaged → as-repaired/as-remediated

Continuation of Table 3.1

1	2	3	4
Engineering risk	Reliability/safety (probability × consequences)	P_i – probability of failure/degradation for element i (ML + physical models); S_i – consequences of failure (safety/lack of accessibility/downtime), damage scale	$R_i{}^\wedge eng = P_i \cdot S_i$; P_i – ML + physics; S_i – consequence matrices/risk classes
Eco-risk	Compliance with standards and regulations	c, A, T – contaminant concentration, impact area/volume, exposure time	$R_i{}^\wedge eco = \varphi(c, A, T)$ the specific φ is defined in the remediation methodology; "compliance vs exposure"
Network/node effect in transport and logistics infrastructure	Impact on the logistics corridor/transport hub	ΔL – network effect on a linear corridor (change in flow/travel time/detours/resilience); $\Delta Node$ – node effect (throughput of a transport hub, redundancy)	$\Delta L = \text{g\_net}(\Delta\text{flow}, \Delta\text{traveltime, detours, resilience})$; $\Delta Node = \text{g\_node(throughput, redundancy/centrality)}$
Prioritization of remediation/reconstruction/restoration measures	Unified intervention priority	w_1, w_2, w_3 – weights for aggregating prioritization criteria (configured by the public administrative body/customer)	$\mathit{\Pi}_i = w_1 \cdot R_i{}^\wedge eng + w_2 \cdot R_i{}^\wedge eco + w_3 \cdot (\Delta L \text{ or } \Delta Node)$; w is calibrated by the governing body; a multi-objective problem formulation is possible
Eco-Gate	Mandatory remediation when threshold contaminant pollution norms are exceeded	$R_i{}^\wedge eco$ – environmental risk for element/segment i; θ_eco	If $R_i{}^\wedge eco > \theta\_eco \Rightarrow$ remediation is mandatory (before and/or together with reconstruction/repair, or decommissioning); commissioning of the facility into operation is impossible without eco-evidence
4D/5D planning	Analysis of access to the remediation/reconstruction/restoration site; demining/technical-and-technological conditions/weather conditions/time windows	$h(\ldots)$ condition; θ_safe *threshold*	If access to the facility for executing the protocol of measures is not ensured $\Rightarrow$ blocking the start of works
Execution of the work protocol → evidence base for control and audit	Closing tasks by evidence (CDE)	photos/videos, LiDAR/point clouds, environmental samples, as-built models, technical and financial documentation	Audit-Gate: closure ⇔ the CDE contains as-repaired & as-remediated with geo-referencing, timestamps, and links to the element/segment of the infrastructure facility

Continuation of Table 3.1

1	2	3	4
Post-monitoring/training	Self-improving loop	new events d'	Repeated surveys/sampling → updating x_i, retraining CV/ML, recalibrating Gate thresholds, updating maintenance plans for transport and logistics infrastructure facilities

The **Table 3.1** presented above is structured in such a way as to capture the key managerial invariants of APRe-TISRM:

a) what exactly enters at each stage (key variables);

b) which rule is applied, indicating the formula and/or specifying specific conditions;

c) the managerial effect that is achieved as a result of the actions undertaken.

Thus, BIM confirms its significance as a foundation, Digital Twin – as an operational "mirror" through synchronization of data on the state of facilities and the implementation of the selected protocol scenarios of remediation/reconstruction/restoration of transport and logistics infrastructure facilities, and the CDE – as an environment of interoperability, versioning and audit.

3.4 BIM/DT as the core of APRe-TISRM: verification of interoperability, significance for ensuring transport safety, and the BOR-Index

Within APRe-TISRM, which covers a set of interconnected and mutually influencing structural elements such as Surveillance & Diagnostics → BIM/Digital Twin → BPMN + 4D/5D → Evidence/CDE, it is precisely BIM/Digital Twin that act as the semantic and operational core. A critical condition for the operability of such a contour is interoperability, namely, the ability of heterogeneous systems and data, including IFC/BCF/BSDD, OGC/INSPIRE, CDE/API, etc., to pass the entire path from the source data to the decisions made and the evidentiary database confirming the implementation of the work protocol without losses and delays. It should be emphasized that losses during exchange and breaks at the junctions S&D ↔ BIM/DT ↔ BPMN/4D/5D significantly worsen safety, increase time and cost, and also negatively affect the completeness of evidence.

An in-depth study of this issue confirmed the primary role and significance of interoperability. In a general understanding, interoperability constitutes the ability to automatically, safely and unhinderedly exchange interpretable data between devices and systems in an information-and-technology network in a standardized manner without technical limitations [18].

In the authors' opinion, assessing interoperability is one of the significant parameters of APRe-TISRM, since it makes it possible to connect the logic of the theoretical linkage S&D → BIM/DT → 4D/5D → CDE with practice, taking into account safety, time, cost, commissioning of infrastructure facilities into operation, which makes it possible to form an objective basis for ranking, financing and scaling BIM-oriented remediation for both linear and point facilities.

For the purpose of an objective assessment of interoperability, the authors emphasized the key aspects:

1. *Scope of coverage: linear vs point infrastructure facilities.*

As was indicated earlier, transport and logistics infrastructure covers linear facilities (including roads, rail tracks, subway lines, etc.) and point facilities (including bridges, tunnels, railway stations, transport hubs, logistics centers, terminals, seaports, airports, etc.) [19].

For linear facilities, the key aspects, in the monograph authors' view, are: chainage and dynamic segmentation, the continuity requirements of remediation/reconstruction/restoration works, routing of crews as well as equipment taking into account the availability of time windows, metrics of the load of the transport and logistics network, accessibility of facilities, and also the time and required resource provision for carrying out the necessary measures. In turn, for point infrastructure facilities, the depth of IFC hierarchies and domain MVDs, distribution by 4D/5D stages, and assessment of the criticality of load on a transport and logistics hub (throughput, redundancy, centrality) are of significant importance and role. In this regard, identification of risk profiles and the corresponding specific data necessitates separate verification and validation of interoperability for linear infrastructure facilities and separately for point infrastructure facilities.

In the context of this study, verification of interoperability is the answer to the question: "Do we correctly understand/interpret the obtained data about the infrastructure facility?". In turn, validation of interoperability is the answer to the question: "Do our integrated exchanges and processes S&D ↔ BIM/DT ↔ 4D/5D/BPMN actually work as intended and produce the required effect?" It should be emphasized that they are closely and end-to-end interrelated: without successful verification, valid effects are unstable and ultimately non-auditable, and without validation, the completed verification remains formal. However, together they transform BIM/DT from a "showcase" into an operational core for managing remediation and restoration for linear and point infrastructure facilities.

2. *Interoperability V&V framework (verification and validation).*

Four levels of interoperability and their corresponding checkpoints were examined in this study, namely:

– syntactic, which focuses on assessing the correctness of IFC/BCF/BSDD and OGC/INSPIRE formats and schemas, as well as exchange profiles/MVDs and validators;

– semantic, which consists in analyzing the consistency and comparability of defect types/codes/dictionaries for linear and point infrastructure facilities, as well as the accuracy of Pixel/Track → IFC/chainage mapping;

– process, oriented toward assessing consistency with BPMN orchestration, gate logic (including Confidence/Eco/Safety/Audit), statuses, as well as routes of remediation/reconstruction/restoration measures;

– operational, which focuses on assessing the causes and facts of delays, evaluating transaction reliability, and resilience under conditions of unstable communications and connectivity. In addition, the degree of completeness and traceability of evidence is assessed.

It is possible to note that for each level, the corresponding metrics are records: Δ*Geom*/Δ*Attr* (round-trip losses), MapAcc (mapping accuracy), Latency (event → → DT → task), GatePass% (percentage of cases that passed the gates), Traceability (links evidence ↔ element/segment of the facility ↔ version), API-Reliability, CDE-Conformance. These indicators are aggregated into the I-Score (0…1) – an integral assessment of interoperability with calibratable weights and thresholds.

3. *Link between interoperability, safety, and the BOR-Index.*

In APRe-TISRM, it is possible to define safety as the primary priority (safety-first): through strict thresholds of the residual risk level at the level of elements and the required network accessibility/LOS, as well as through the Safety-Gate, namely through the possibility of safe access to the infrastructure facility, including by means of demining and carrying out remediation measures for soil, water and air, ensuring personnel-safe conditions for performing restoration works, as well as weather and technological conditions. In the monograph authors' view, interoperability is a predictor of safety (including transport safety), since it determines the accuracy and timeliness of defect mapping in the DT, the correctness of prioritizing the required remediation/reconstruction/restoration works, and the quality of the 4D/5D plan.

To objectify the assessment, it is proposed to use an integrated *BOR-Index (BIM-Oriented Remediation Index)* – an integral KPI of the quality of BIM-oriented remediation/restoration (0…1), which is based on normalized sub-indices, namely: the degree of reduction of engineering risk (S_1), eco-compliance (S_2), compliance with 4D parameters (S_3) and 5D parameters (S_4), DT consistency (S_5), completeness of evidence (S_6), and the degree of impact on the transport and logistics network (S_7).

Note that interoperability will affect the BOR-Index directly through S_5 (DT-fidelity) and S_6 (evidence completeness), and also indirectly through S_1/S_7 (assessments of risk accuracy as well as network accessibility). In practice, an increase in the I-Score leads to an increase in the BOR-Index, which is expressed in shorter delays in managerial decision-making, less rework, better manageability of 4D/5D, and faster auditable commissioning of restored infrastructure facilities into operation.

The mathematical formalization of the BOR-Index is as follows

$$BOR = \underbrace{G_{safe} \cdot G_{eco} \cdot G_{audit} \cdot G_{conf}}_{mandatory\ gates} \left(\sum_{k=1}^{7} \omega_k \cdot s_k \right), \sum_{k=1}^{7} \omega_k = 1, \omega_k \ge 0 . \tag{3.1}$$

The decomposition of the BOR-Index formula with gates (indicator functions) is presented below:

1. *Safety-Gate.*

$$G_{safe} = 1\left\{ \forall_i \in A : R_i^{res} \le \bar{R}_i \right\} \cdot 1 \left\{ \begin{matrix} \forall_j \in W_{shed} : a_j \le s_j \le b_j - t_j \wedge Access_j = \\ = 1 \wedge Demining_j = 1 \wedge Wether_j = 1 \end{matrix} \right\}. \tag{3.2}$$

2. *Eco-Gate.*

$$G_{eco} = 1\left\{ \forall_i \in A_{eco} : R_i^{eco} \le \Theta_{eco} \right\} \wedge 1\left\{ \forall_i \in A_{eco} : c_i \le C_i^{\max} \wedge T_i \le T_i^{\max} \wedge A_i \le A_i^{\max} \right\}, \tag{3.3}$$

where $R_i^{eco} = \varphi\left(c_i, A_i, T_i\right); C_i^{\max}, T_i^{\max}, A_i^{\max}$ – approved limits based on standards/permits.

3. *Audit-Gate.*

Let's define the completeness and traceability of the evidence base in the CDE for all tasks being closed for remediation/reconstruction/restoration of transport and logistics infrastructure facilities

$$G_{audit} = 1 \left\{ \begin{matrix} \forall_i \in W_{closed} : \underbrace{EvidComp_j \ge \tau_{evid}}_{\substack{completeness\ evidence \\ photo/video/LiDAR/eco\text{-}probes}} \wedge \underbrace{Trace_j = 1}_{\substack{connection\ to \\ IFG\text{-}GUID/chainage+ \\ +geo/time+signatures}} \wedge \underbrace{CDEconf_j \ge \tau_{cde}}_{\substack{ISO\ 19650:\ versions/statuses \\ WORM\text{-}logs}} \end{matrix} \right\}. \tag{3.4}$$

4. *Confidence-Gate.*

$$G_{conf} = 1\left\{ \forall d \in D_{used} : \left(u(d) \ge \Theta_c \wedge \varepsilon(d) \le \Theta_e \vee \mathrm{HIL}(d) = 1 \right) \right\}, \tag{3.5}$$

where $u(d)$ – the degree of confidence of the object detection; $\varepsilon(d)$ – the registration error; $\mathrm{HIL}(d) = 1$ – the fact of passing mandatory verification by specialists in the case of assessing "borderline" events.

The scheme presented in **Fig. 3.2** serves as a framework for linking the metrics described above. Thus, on the input contour S&D → CDE/DT, the I-Score is assessed for: Syntax/Formats and Semantics (registration and mapping accuracy); at the Prioritization/Planning junction – the I-Score for: Process/Operational (latency evt → DT → task, gate compliance); at the output Execute/QA → Post-Monitoring – the I-Score for: Evidence/CDE (completeness/traceability of evidence). All interoperability levels shown in the figure are aggregated into the BOR-Index, which makes it possible to directly identify the impact of each node of the scheme on the target effect of remediation and restoration of infrastructure facilities of the transport and logistics system.

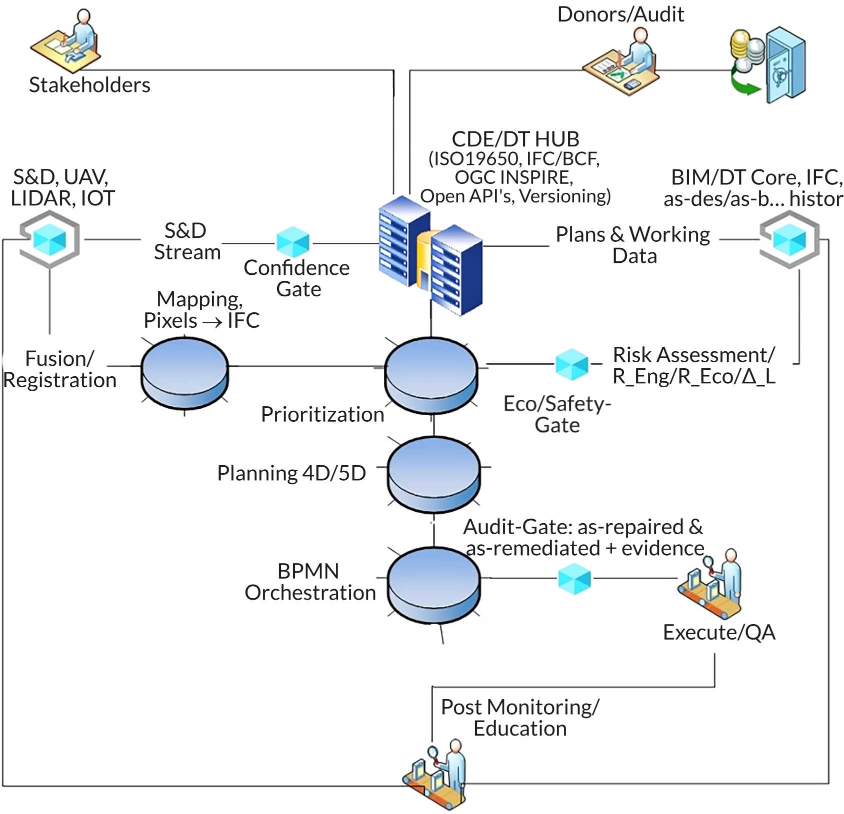


Fig. 3.2 Architectural map of APRe-TISRM flows

Next, let's move from the formal decomposition of the BOR-Index to its visual interpretation, since even a correct mathematical formalization remains a "black box" for various groups of stakeholders (let's refer to representatives of public administrative bodies, investors, IT specialists, engineers, contractors, etc.). Visualization makes it possible to interpret accumulated data and the calculated indicators in a clear way, namely:

1) it explicitly shows where exactly losses arise in the contours S&D → BIM/DT → → Ops (interoperability analysis by levels);

2) it explains which mechanism of improving interoperability is transformed into an increase in BOR (let's refer to the decomposition of cause-and-effect contributions);

3) it allows quick comparison of groups of infrastructure facilities (linear vs point) in terms of their weak/strong zones.

This is essential for the purposes of prioritizing remediation, reconstruction/restoration works, selecting the optimal scenario, protocol of measures, budget, as well as the timelines for its implementation.

Of all possible options, it is feasible to select the following visualization forms:

– *Heatmap*, which provides a "diagnosis" by interoperability levels (Syntax/Formats, Semantics, Process/BPMN + Gates, Operational, Evidence/CDE) and metrics (including Latency, MapAcc, Traceability), showing the specific breakpoints in the APRe-TISRM framework chain;

– *Waterfall*, which answers the question "Why does the BOR index grow?", i.e., it makes it possible to see the contribution of ΔS_5 (DT-fidelity), ΔS_6 (evidence completeness) and indirect $\Delta S_1/\Delta S_7$ (timeliness/accuracy), linking the driver (interoperability) and the result (BOR);

– *Radar (Linear vs Point)*, which makes it possible to compare profiles and see where linear transport and logistics infrastructure facilities fall behind point facilities (or vice versa).

In the monograph authors' view, together these three charts form a clear bridge "from formalization to making rational managerial decisions".

For calculations and charting, the authors used Python (Matplotlib) scripts in a Jupyter-type computing environment. This approach is reproducible (script versions and the source interoperability matrices are recorded), transparent for audit (all data transformations are documented), and vendor-neutral with respect to specific CDE/IFC validation vendors – normalized matrices/metrics agreed with the methodology presented above are provided as input. Numerical values in the charts are marked as reference design values and are subject to refinement in pilots.

In summary, it is possible to state that visualization in this context acts as a tool for managing the process as a whole, including managing information, coordinating all project participants, responsibility, resource provision, risks, time, cost, and the results of remediation/reconstruction/restoration of transport and logistics infrastructure facilities. In the authors' conviction, this set of visualizations will make it easier to defend project decisions before public administrative bodies, investors, donors and contractors, while minimizing the level of semantic ambiguity.

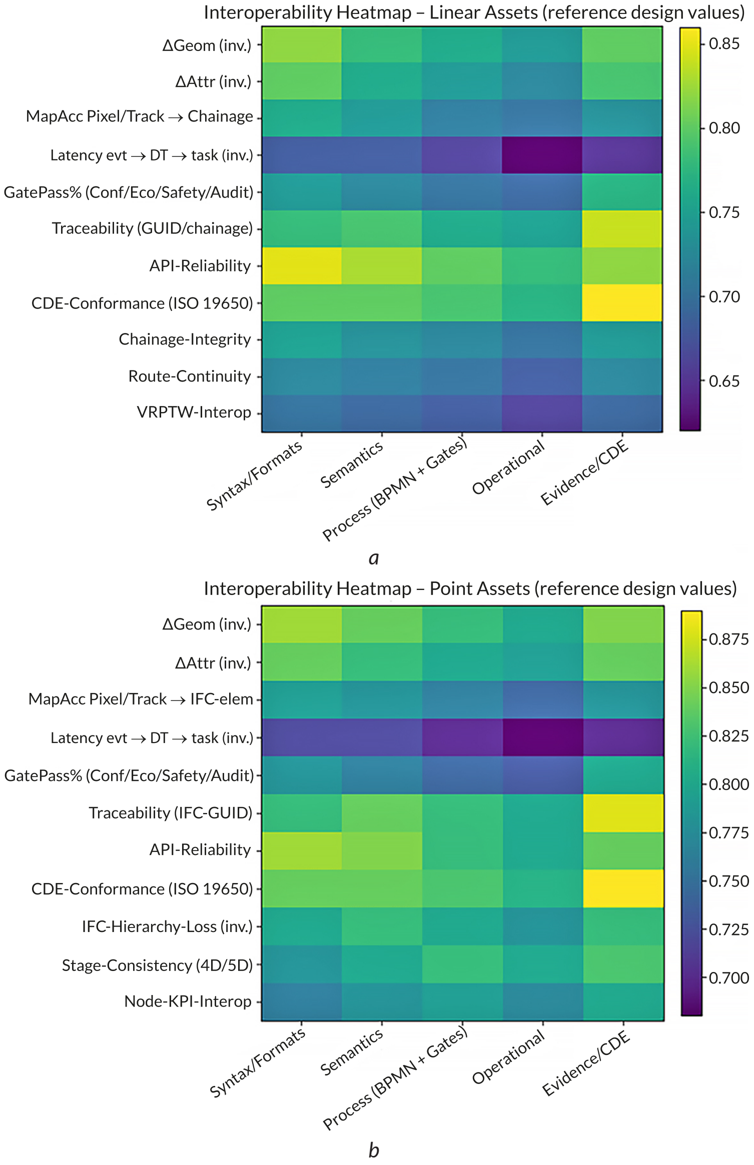
The heatmaps presented in **Fig. 3.3** show where exactly the interoperability chain breaks, and not simply which class of transport and logistics infrastructure facilities is better or worse. Based on these data, a general conclusion can be made: for linear infrastructure facilities, the weak point is addressing, routing, and delays, and for point facilities – the consistency of the stages of remediation/reconstruction/restoration works and the KPI of transport hubs. These are the growth points of the BOR-Index.

By the aggregate interoperability indicator, point infrastructure facilities outperform linear ones, namely: I-Score_Point = 0.805 versus I-Score_Linear = 0.746. The weakest point for both groups is the operational delay "event → DT → task": the row average for Latency (inv.) for linear infrastructure facilities is ≈ 0.66 (values in the matrix respectively: 0.68/0.68/0.66/0.62/0.65), for point infrastructure facilities is ≈ 0.70 (values in the matrix respectively: 0.72/0.72/0.70/0.68/0.70).

The Waterfall (Linear vs Point) presented in **Fig. 3.4** shows which "building blocks" the increase in the BOR-Index is composed of due to the growth of interoperability. As is seen, the main contribution is made by ΔS_5 (DT-fidelity) and ΔS_6 (evidence completeness), and the indirect contribution – by $\Delta S_1/S_7$, which characterize timeliness and accuracy. For linear infrastructure facilities, the total increase amounts to ≈ +0.050 (= 0.030 + 0.015 + 0.005), for point infrastructure facilities – ≈ +0.060, i.e., with an equal improvement of interoperability, point transport and logistics infrastructure facilities obtain a slightly larger gain.

Based on this, it can be concluded that the maximum effect on the BOR index is produced by investment in the accuracy and relevance of the DT (reducing the gap "as-is" ↔ "DT") and the completeness of the evidence database in the CDE (traceable photos/videos/scans/environmental samples, etc.). For linear infrastructure facilities, it is additionally necessary to critically strengthen the chainage mapping chain and the VRPTW integration in order to reach the level of point infrastructure facilities. These waterfalls make it possible to answer the question: where to direct efforts first in order to transform I-Score growth into a tangible increase in the BOR-Index.

In the presented radar chart (**Fig. 3.5**), it is clearly visible that point infrastructure facilities consistently outperform linear transport and logistics infrastructure facilities across all five interoperability levels: the differences amount to ~0.04–0.06 on each axis (especially in Operational and Process (BPMN + Gates)). The value labels show: Linear ≈ 0.71–0.77, Point ≈ 0.77–0.82, i.e., the lag of linear infrastructure facilities is systemic rather than local.


Interoperability Heatmap – Linear Assets (reference design values)

Interoperability Heatmap – Point Assets (reference design values)

Fig. 3.3 Heatmaps of I-matrices for linear (*a*) and point (*b*) transport and logistics infrastructure facilities

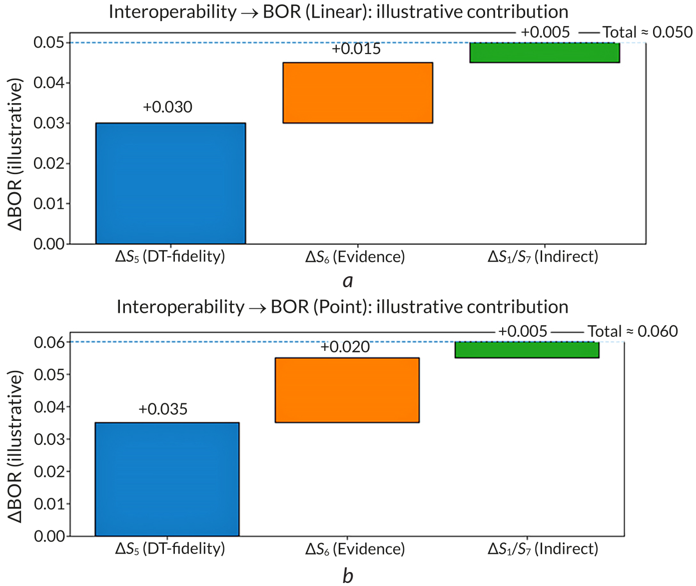


Fig. 3.4 "Waterfall" of effects: how interoperability increases BOR:
a – linear transport and logistics infrastructure facilities; *b* – point facilities

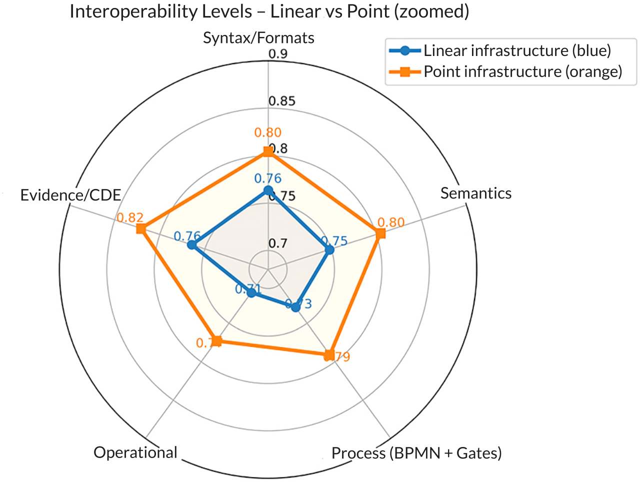


Fig. 3.5 Interoperability of S&D → BIM/DT → Ops by levels: comparison for point and linear transport and logistics infrastructure facilities

In practice, this means prioritizing the undertaken measures for linear infrastructure facilities precisely in the "middle of the contour", namely, reducing latency and improving semantic mapping/process gates, since this is where the most significant breaks for the BOR-Index are. It is important to note that the radar chart makes it possible to set a vector for a roadmap oriented toward rapid elimination of process-and-operational failures for linear infrastructure facilities, while maintaining the achieved high level of Evidence/CDE for point infrastructure facilities.

3.5 Benchmark case (Italy): transferable BIM/DT practices for remediation/reconstruction/restoration of infrastructure facilities in post-disaster territories

In order to substantiate the expediency of the BIM-oriented remediation approach proposed by the authors, the Genoa bridge restoration case (Italy) was analyzed in depth and comprehensively – a still rare, yet well-documented example where the linkage BIM ↔ Digital Twin ↔ 4D/5D ↔ evidence-based commissioning of an infrastructure facility actually worked under the conditions of a crisis restoration project. Implementation of this benchmark is absolutely expedient in the context of eliminating the consequences of natural and man-made disasters, as well as eliminating the consequences of military activity, since it:

– demonstrates a paradigm shift, namely, the transition from BIM as a design showcase to an operational core for managing time, cost, quality and safety;

– provides an evidence base for stakeholders, namely, real facts of applying the BIM/DT linkage in the urgent restoration of a critical infrastructure facility;

– directly correlates with the developed metrics, namely, this case makes it possible to test in practice the BOR-Index and I-Score proposed by the authors for implementation;

– covers validation of the group of point transport and logistics infrastructure facilities, since the Genoa bridge is a point asset with a high level of node criticality.

Description of the benchmark case: restoration of the bridge in Genoa (Viadotto Genova – San Giorgio, Italy).

Situation and scale. On 14 August 2018, a bridge span of approximately ≈ 210 m collapsed on the Morandi (Polcevera) viaduct, which as a result led to 43 fatalities, the shutdown of three railway lines, as well as significant transport-logistics and economic losses for Genoa itself and the region as a whole. A decision was made, as a replacement for the destroyed bridge, to build the new Genoa – Saint George

Bridge (Viadotto Genova – San Giorgio), which represents a mixed steel-and-concrete structure with a total length of 1,067 m and a width of approximately ≈ 30.8 m, supported by 18 reinforced-concrete piers. Sensor systems and robotic monitoring systems were incorporated into this infrastructure facility. The project cost amounted to about 202 million EUR. The opening of the facility took place on 3 August 2020, and the opening of traffic took place on 4 August 2020.

Technical and managerial parameters of the project. This project was implemented in an accelerated restoration mode with parallel dismantling of old structures, and the construction of the foundation started simultaneously with the completion of as-built design. Italferr (an engineering subsidiary company of Ferrovie dello Stato Italiane) was selected by the Pergenova consortium to develop the project. It should be noted that during design, 34 BIM models were synchronized into a single package. In order to meet extremely tight deadlines (initially, about three months were allocated for design), a BIM/DT approach with an open CDE environment on ProjectWise was implemented; MicroStation, OpenRoads, OpenBuildings Designer, Navigator, Descartes, and SYNCHRO (4D) were used. In addition, the geocontext of the data accumulated during project implementation was organically integrated, namely, LiDAR surveys of the terrain and orthophotos; digital surface model data of the relief and the base of the bridge structure for checking pile depths and aligning design decisions with actual elevations.

As a result, the following effects were obtained: optimization of the coordination process between project participants, automation of 4D scenarios, reduction of clashes, and increased accuracy of estimates and set planned indicators (**Fig. 3.6**).

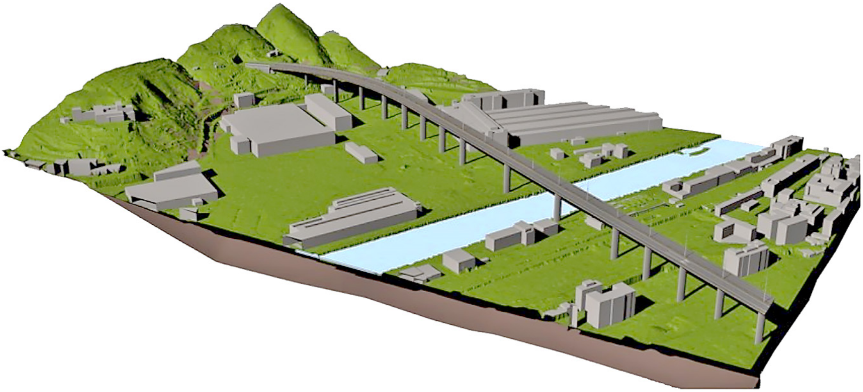


Fig. 3.6 The BIM information digital model for the Polcevera Viaduct
Source: [20]

Composition of participants and roles. Architectural concept – Renzo Piano; builders – Webuild and Fincantieri; operator/concessionaire – Autostrade per l'Italia; technical supervision and certification functions – RINA (a contract was signed for an amount of about 14 million EUR). Commissioning was carried out with the participation of regional government authorities. It should be noted separately that robotic inspection tools developed by the Istituto Italiano di Tecnologia were installed at the facility.

Chronology of the "compressed cycle". The public presentation of the concept took place in September 2018; intensive design-and-survey works → dismantling of the remaining structures in 2019; the "first stone" was laid on 25 June 2019; the main concreting of the deck slab was completed in June 2020.

As a result, intelligent 4D coordination of works on restoring the infrastructure facility made it possible to meet the target horizon of ≈ 15 months of construction.

Context and transferability boundaries in APRe-TISRM. In the Italian case, the linkage S&D → BIM/DT → Ops was built as a single managerial contour in which surveillance was immediately converted into manageable decisions. At the input, S&D provided multi-sensor surveying (UAV RGB/video, laser scanning, periodic inspections) with subsequent normalization and consolidation of data streams in a common CDE. In turn, at the BIM/DT layer, a high-detail model with specified LOD/LOI was maintained for critical nodes and in a mode of continuous synchronization of the states "as-designed ↔ as-built". The digital twin performed the role of a "sense organ" and a coordination plane for 4D/5D analysis with subsequent design and planning. Next, in the Ops layer, a 4D chronology of the executed works and 5D estimates were launched, and processes were orchestrated through BPMN with formalized Confidence/Eco/Safety/Audit gates. These gates served as "admission points", allowing the quality of data and the risks of starting/completing works within the specified time frames to be cross-aligned, with record of the evidence base in the CDE. As a result, an end-to-end cycle "data → semantics → action" was created and successfully tested, which made it possible to minimize time delays, significantly increase traceability, and ensure evidence-based commissioning of the facility into operation.

It should be especially emphasized that in the Italian project BIM/Digital Twin acted not simply as one of the data sources, but as the semantic and operational center of the entire contour S&D → BIM/DT → Ops. First, BIM/DT made it possible to ensure addressability and traceability. That is, each signal from S&D (data received from UAVs, LiDAR, change-detection, etc.) underwent normalization in the CDE and was then linked to IFC elements (via GUID, MVD validation), which helped eliminate hanging defects without geometric-and-semantic addressing. Second, the digital twin maintained continuous synchronization of the facility's states (as-designed → as-built → as-damaged → as-repaired/as-remediated) and served as a coordination plane for 4D/5D, where each model update was automatically translated into the planned project timeline and budget. Third, BCF flows and BPMN gates in BIM/DT performed the role of a kind of process "arbiter". Finally, BIM/DT performed the role of the evidence base center: the "as-repaired & as-remediated" data were recorded in the CDE with linkage to the corresponding photo/video data, as well as data of technical expertise, environmental samples, and financial audit, which as a result made it possible to ensure the reproducibility of a direct link – "metric → artifact".

The case studied was interpreted in **Table 3.2** as a transferable correspondence table in terms of the parameters "data → tools → metrics → decisions", where each type of observation has a standard route in the CDE, semantic addressing in BIM/DT, and specific initial quality metrics.

Table 3.2 Generalized correspondence table relevant to APRe-TISRM

Block (data/tools)	Used sources and means	Processing → → integration	Target metrics/artifacts/ transfer characteristic
1	2	3	4
Geometry and condition	UAVs (RGB/video), ground/airborne LiDAR, photogrammetry, periodic inspections of the infrastructure facility	Registration of point clouds; alignment with BIM (as-built/as-damaged); upload to the CDE	ΔGeom, ΔAttr, scan density/coverage; deviation reports. Rule: each surveying cycle ↔ DT update; deviations automatically generate BCF issues
Semantics and addressing	IFC models, dictionaries, BCF issues	GUID traceability; mapping of S&D events → elements/ nodes of the infrastructure facility; MVD validation	MapAcc (Pixel/Track → → IFC), attribute completeness, % of valid GUIDs. Rule: no GUID – no task. Planning is performed only for events linked to IFC
Processes and integrations	CDE (in accordance with ISO 19650), BIM ↔ 4D/5D ↔ supply/ logistics API, starting BPMN engine	Auto-synchronization of statuses; orchestration of implemented measures and commissioning of the facility into operation; analysis of protocols of planned works	GatePass% (Conf/Eco/ Safety/Audit), status traceability, SLA compliance. Rule: gates as predicates: without Conf/Eco/Safety-OK status, tasks do not start; without Audit evidence, they do not close
Diagnostics and prognosis	Change detection, automated/semi-automated classification, engineering calculations of RUL/risk	Consolidation of conclusions in the DT; updating tolerance curves; task routing	Accuracy (F1/IoU), Latency evt → DT → task, RUL MAE/MAPE. Rule: from pixel to managerial decision: diagnostic conclusions automatically form 4D/5D tasks

Continuation of Table 3.2

1	2	3	4
Evidence and commissioning	Photos/videos, point clouds, certificates of completed works, environmental samples, etc.	Linking evidence to elements/nodes; "as-repaired/as-remediated" version in the CDE	Evidence completeness, audit trail, reproducibility. Rule: closure = evidence + version in the CDE: without this, the Audit-Gate does not pass
Operational readiness	4D/5D plans, supply/routing of construction-and-repair crews	Updating schedules as executed; VRPTW with account of access windows; accounting for Safety constraints	Timeliness (S_7), "plan vs actual" deviations, availability (uptime). Rule: latency down, uptime up: prioritize optimization of delays at the Ops stage

Thus, in the table presented above, each block of tools and data is closed on BIM/DT – from a pixel and a point cloud to a manageable IFC element, from the status of a structural element of an affected infrastructure facility as a result of emergency events to the plan of remediation/reconstruction/restoration works and to evidence, which is what makes possible the implementation of this case as transferable into APRe-TISRM.

3.6 Conclusion

As a result of the conducted study, APRe-TISRM was formed and substantiated – an architectural-and-process model of an end-to-end contour Surveillance & Diagnostics → BIM/Digital Twin → 4D/5D + BPMN → execution → post-monitoring, oriented toward restoration and remediation of transport and logistics infrastructure facilities. It was substantiated that BIM/DT is not a "showcase" of data of a linear or point facility, but performs the role of a semantic-and-operational core that links pixels/point clouds with manageable IFC elements and automatically translates updates of the facility state in linkage with 4D (time) and 5D (cost) of remediation/reconstruction/restoration. The study proposed the I-Score metrics for assessing interoperability and the BOR-Index as a target integral indicator of safety – time – cost – quality – evidence – timeliness of remediation/reconstruction/restoration works, providing a unified basis for data interpretation for all stakeholders. A comparative analysis of linear and point infrastructure facilities was carried out: for the former, the key failures are located in the chainage/operational latency chain (S_7), for the latter – in maintaining high DT accuracy and evidence completeness (S_5/S_6), which determines the difference in priorities of implementing the work protocol. The Genoa bridge restoration case was studied in order to analyze the possibility of transferability of the practice of restoring an infrastructure facility located in post-disaster territories. This benchmark will be especially relevant and significant for countries that have suffered from emergency events of a natural and man-made nature, as well as from military activity. Thus, the aim of the study – to build a holistic methodology and management architecture for restoration and remediation based on image recognition and BIM/DT – was achieved, and the tasks of theoretical substantiation, formalization, metrics and benchmarking were completed. In the monograph authors' view, the APRe-TISRM model can be used as a pilot version for approbation on infrastructure facilities of Ukraine after the end of the active phase of hostilities, ensuring verifiable, accelerated and safe restoration of the national transport and logistics system.

The authors plan to conduct an in-depth study of the possibilities of 6D (operations) based on BIM/DT, where the digital twin will act as an operational core for managing energy consumption, operating modes and the technical condition of infrastructure facilities in real time. Research is also envisaged into algorithms of resilient operational management – MPC/RL – and the development of an extended BOR index, allowing quantitative assessment of the effect of 6D interoperability through reduction of OPEX/CO_2e, increase of uptime, and improvement of safety.

Conflict of interest

The authors declares that there is no conflict of interest regarding the content of this paper, including any financial aspects related to the conduct of the research, the acquisition and use of its results, or any non-financial personal relationships.

Financing

The study was performed without financial support.

Data availability

The data that supports the findings of this study will be made available by the authors on reasonable request.

Use of artificial intelligence statement

The authors state that artificial intelligence was used in this article only for partial translation of the text and correction of academic style.

Acknowledgments

The authors received no specific support from individuals or organizations that should be acknowledged beyond their institutional affiliations stated in the manuscript.

Authors' contributions

Tetiana Cherniavska: Conceptualization, Development of the theoretical and methodological framework (APRe-TISRM), Formal analysis, Integration of BIM/Digital Twin and Surveillance & Diagnostics concepts, Writing – original draft, Writing – review & editing.

Bohdan Cherniavskyi: Methodology, Data curation, Software and computational modeling, Image recognition and analytics (CV/ML), Visualization (heatmaps, indices, benchmarking diagrams), Writing – review & editing.

Oksana Zghurska: Investigation, Literature review, Analysis of post-conflict and post-disaster infrastructure recovery practices, Interpretation of results, Writing – review & editing.

Serhii Kasian: Domain expertise in transport and logistics infrastructure, Validation of engineering assumptions, Risk and safety analysis, Formal analysis, Writing – review & editing.

Kateryna Nakonechna: Methodological support, Analysis of process reengineering (BPMN, 4D/5D planning), Integration of management and operational aspects, Writing – review & editing.

Yaroslava Mudra: Case study analysis (benchmarking, including international experience), Data interpretation, Project administration, Coordination of interdisciplinary inputs, Writing – review & editing.

All authors contributed to the scientific content of this study, jointly developed the conceptual idea of BIM-oriented remediation and process reengineering for transport infrastructure recovery, participated in discussions and validation of results, and approved the final version of the manuscript.

References

1. Abdelalim, A. M., Essawy, A., Sherif, A., Salem, M., Al-Adwani, M., Abdullah, M. S. (2025). Optimizing Facilities Management Through Artificial Intelligence and Digital Twin Technology in Mega-Facilities. Sustainability, 17 (5), 1826. https://doi.org/10.3390/su17051826
2. Saeed, Z. O., Almukhtar, A., Abanda, H., Tah, J. (2021). BIM Applications in Post-Conflict Contexts: The Reconstruction of Mosul City. Buildings, 11 (8), 351. https://doi.org/10.3390/buildings11080351
3. Adopting Digital Twin Solutions for Genoa Bridge Reconstruction Proves to be Economical and Efficient. Geospatial World Prime. Available at: https://geospatialworld.net/prime/case-study/aec/adopting-digital-twin-solutions-for-genoa-bridge-reconstruction-proves-to-be-economical-and-efficient/
4. Gordo-Gregorio, P., Alavi, H., Forcada, N. (2025). Decoding BIM Challenges in Facility Management Areas: A Stakeholders' Perspective. Buildings, 15 (5), 811. https://doi.org/10.3390/buildings15050811
5. Cherniavskyi, B.; Cherniavska, T. (Ed.) (2025). Digitalization of crisis management remediation: assessment of implementation and development prospects. Economy in the era of digital transformation: trends, opportunities and perspectives. Tallinn: Scientific Route OÜ, 51–73. https://doi.org/10.21303/978-9908-9706-0-8.ch3
6. Wu, D., Zheng, A., Yu, W., Cao, H., Ling, Q., Liu, J., Zhou, D. (2025). Digital Twin Technology in Transportation Infrastructure: A Comprehensive Survey of Current Applications, Challenges, and Future Directions. Applied Sciences, 15 (4), 1911. https://doi.org/10.3390/app15041911
7. Cherniavskyi, B.; Cherniavska, T. (Ed.) (2025). Information technologies in scenario-based modeling of post-conflict territory remediation: from express sanitation to sustainable recovery. Ecological systems modeling. Tallinn: Scientific Route OÜ, 74–95. https://doi.org/10.21303/978-9908-9706-6-0.ch4
8. Cherniavskyi, B., Blakyta, H., Susidenko, V., Andreichenko, A., Remyha, Y., Podmazko, O.; Cherniavska, T. (Ed.) (2025). Innovative technologies and digital models in the post-war recovery of the transport and logistics system of Ukraine. Economy in the Era of Digital Transformation: Trends, Opportunities and Perspectives. Tallinn: Scientific Route OÜ, 110–143. https://doi.org/10.21303/978-9908-9706-0-8.ch5
9. Elazouni, A., Salem, O. A. (2011). Progress monitoring of construction projects using pattern recognition techniques. Construction Management and Economics, 29 (4), 355–370. https://doi.org/10.1080/01446193.2011.554846

10. Remedial Action Work Plan (2022). Hunter Army Airfield, G.
11. Shen, C., Chou, C.-C. (2010). Business process re-engineering in the logistics industry: a study of implementation, success factors, and performance. Enterprise Information Systems, 4 (1), 61–78. https://doi.org/10.1080/17517570903154567
12. Cherniavska, T., Cherniavskyi, B. (2025). Digital reconstructor: Integration of digital twins for the reconstruction and remediation of war-affected territories in Ukraine. UKLO Proceedings, 1 (1), 137–145. https://doi.org/10.20544/AISC.1.1.25.P13
13. Seidaliyeva, U., Ilipbayeva, L., Utebayeva, D., Smailov, N., Matson, E. T., Tashtay, Y. et al. (2025). LiDAR Technology for UAV Detection: From Fundamentals and Operational Principles to Advanced Detection and Classification Techniques. Sensors, 25 (9), 2757. https://doi.org/10.3390/s25092757
14. Hosamo, H. H., Rolfsen, C. N., Zeka, F., Sandbeck, S., Said, S., Sætre, M. A. (2024). Navigating the Adoption of 5D Building Information Modeling: Insights from Norway. Infrastructures, 9 (4), 75. https://doi.org/10.3390/infrastructures9040075
15. Tebourbi, H., Nouzri, S., Mualla, Y., El Fatimi, M., Najjar, A., Abbas-Turki, A., Dridi, M. (2025). BPMN-Based Design of Multi-Agent Systems: Personalized Language Learning Workflow Automation with RAG-Enhanced Knowledge Access. Information, 16 (9), 809. https://doi.org/10.3390/info16090809
16. Cherniavska, T., Cherniavskyi, B. (2024). Architecture-oriented agent-based model (AOAM) for optimizing transport evacuation management and emergency medical assistance in the context of the war in Ukraine: challenges and prospects. CEUR Workshop Proceedings. Available at: https://ceur-ws.org/Vol-3892/paper21.pdf
17. Harclerode, M., Ridsdale, D. R., Darmendrail, D., Bardos, P., Alexandrescu, F., Nathanail, P. et al. (2015). Integrating the Social Dimension in Remediation Decision-Making: State of the Practice and Way Forward. Remediation Journal, 26 (1), 11–42. https://doi.org/10.1002/rem.21447
18. Berg, C. (2024). Interoperability. Internet Policy Review, 13 (2). https://doi.org/10.14763/2024.2.1749
19. Gomes Correia, A., Winter, M. G., Puppala, A. J. (2016). A review of sustainable approaches in transport infrastructure geotechnics. Transportation Geotechnics, 7, 21–28. https://doi.org/10.1016/j.trgeo.2016.03.003
20. The new Genova San Giorgio Viaduct. Elegance, Innovation, Resilience. Implemented Solutions (2022). Gruppo FS Italiane. Available at: https://www.italferr.it/en/technology-and-innovation/BIM/design/genoa-san-giorgio-viaduct.html