sustainability

MDPI

Article

Defining a Digital Strategy in a BIM Environment to Manage Existing Reinforced Concrete Bridges in the Context of Italian Regulation

Angelo Ciccone [1,*], Pompilio Suglia [1], Domenico Asprone [1], Antonio Salzano [2] and Maurizio Nicolella [2]

[1] Department of Structures for Engineering and Architecture, University of Naples Federico II, 80125 Naples, Italy
[2] Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, 80125 Naples, Italy
* Correspondence: angelo.ciccone@unina.it

Abstract: Regulatory activity concerning the management of existing bridges has recently been affected by updates, for instance, in Italy, which calls for a speedy and pragmatic approach based on new technologies such as building information modeling (BIM), when dealing with the survey and risk classification as well as the evaluation and monitoring of structural safety. This paper focuses on the development and integration of a digital solution, based principally on the specific framework developed by the authors, which supports BIM modeling and information management activities, in the structural setting under investigation, through the use of several technologies and tools, namely BIM-authoring, CDE platform and visual programming, in addition to programming in Python. Starting from the organization of a specific BIM object library and the initial data, inserted by means of a custom-made input environment, it was possible to reproduce digital models of bridges in accordance with specific information requirements following the new Level of Information Need setting. The applicability of the proposal is tested on two judiciously chosen real-life cases with different characteristics. Through this implementation, a series of advantages emerge, including expediting traditional procedures for BIM modeling, accessibility and traceability of information—which are constantly updated to support the monitoring of structural safety over time—and the decision-making process related to the bridge management context.

Keywords: existing R.C. bridges; bridge management; BIM modelling; information management; structural regulatory context

Citation: Ciccone, A.; Suglia, P.; Asprone, D.; Salzano, A.; Nicolella, M. Defining a Digital Strategy in a BIM Environment to Manage Existing Reinforced Concrete Bridges in the Context of Italian Regulation. *Sustainability* **2022**, *14*, 11767. https://doi.org/10.3390/su141811767

Academic Editors: Luigi Pariota, Francesco Abbondati and Aliakbar Kamari

Received: 14 June 2022
Accepted: 13 September 2022
Published: 19 September 2022

1. Introduction

Bridges and viaducts, which are used by both rail and road networks, consist of elements that are complex in terms of construction, design, and execution and which are expensive in terms of the resources used in their management, control, and maintenance. As is well known, bridges and viaducts are highly exposed to processes of structural deterioration induced by various climatic conditions, by aging, and by the weight of traffic loads. Consequently, there is an ever-increasing need to improve bridge management [1]. In the event of earthquakes or other natural events, the exposure and vulnerability of a built asset (e.g., existing bridges) must be taken into account. A thorough assessment of whatever deterioration or defects can be made and a subsequent diagnosis and maintenance strategy can be adopted to guarantee the safety, durability, and functionality of the bridge [2]. In Italy, transport networks are characterized by a large number of crossing constructions (e.g., bridges), due to the morphological configuration of the country as well as the presence of waterway networks. This heritage is highly heterogeneous in terms of origin, typology, and characteristics. Obviously, as time goes by, multiple factors linked to the continuous development and evolution of transport networks make it necessary to evaluate the safety of infrastructural assets (principally bridges) in an updated and organized regulatory framework. Considering a lifecycle-oriented approach, for the management and maintenance of bridge safety, the use of new approaches, solutions and digital tools is necessary [1–9]. Among the most applicable digital technologies is building information modeling (BIM). Early concepts related to BIM date back to the 1970s [3], but nowadays, it can be considered as an operational technology for use in the construction sector, aimed at creating, storing, and managing information relating to an asset (e.g., building or infrastructure) during the construction's entire lifecycle. To date, the application of BIM methodologies has mostly involved the context of new projects. However, it can be applied to each phase of the asset life-cycle including the management phases [10–14]. Additionally, in the case of bridges, BIM applications in management and maintenance phases coming relatively late. Given that we have recently started to proceed with the digitalization of existing infrastructure, it is reasonable to expect that in the immediate future, infrastructural heritage will be available in the form of three-dimensional, parametric, and informative models. Hence, for supporting these new methodologies, there has been growing demand in this area. To accomplish this, various tools and technologies (visual programming, IOT, machine learning, and more) can be used. With this aim, the authors develop an all-encompassing digital solution, considering different BIM technologies available today, for supporting parametric 3D modeling activities in addition to the processing, integration, and management of information, in the context of the Italian regulation, regarding existing reinforced concrete bridges.

1.1. Regulatory Context for the Management of Bridges

Bridge management can be understood as the optimal planning of inspection and maintenance activities, with the aim of preserving the value of infrastructure, and thus optimizing costs throughout a given installation's lifecycle while ensuring the safety of users and sufficient quality of service. In the United States, regulation regarding bridge management has involved institutions and organizations such as the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). After other relevant events, bridge management systems (BMS) are adopted, and additional regulations, manuals, and guidelines, regarding the assessment and verification of existing bridges, are issued. In the field of the verification of existing structures, in the case of the United Kingdom, other documents were issued. In Europe, the Council of the European Union included the transport sector in its list of critical infrastructure a few decades ago (*Directive of the Council of the European Union 2008/114 EC*, 2008). In Italy, the regulatory framework is fragmented into various ministerial circulars, specific guidelines, provincial regulations, and stipulations of the various groups operating in the transport sector. With the current NTC2018 and the related Circular of 2019, sensitivity about the structural safety management and maintenance of existing structures has certainly increased. Following the catastrophic events (e.g., occurred on Polcevera viaduct), the regulation framework was updated (e.g., Decree No. 109 of 2018, Law No. 130 of 2018). Mostly, in the context of infrastructure management, regulatory provisions have concerned the institution of the AINOP (*Archivio Informatico Nazionale delle Opere Pubbliche*) and the definition of the LGP approach (Figure 1). Indeed, the AINOP was set up for the census of public civil works pertaining to managing bodies and authorities [7]. It was established to record all the information required for public infrastructural assets (road and railway bridges, tunnels, etc.), present on the national territory, and is managed through a digital platform where information must be organized in sections (according to the type of infrastructure, including road bridges), subsections, and other specific input areas where census data, technical data, economic–financial data, structural monitoring data, maintenance data, works, and others have to be recorded.

The Italian guidelines entitled 'Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti' (LGP) were published by the Superior Council of Public Works (C.S. LL. PP.) and then adopted at a ministerial level (Ministry of Infrastructure and Transport) [15]. As shown in Figure 1b, the LGP multilevel approach is based on the definition of a CdA (Classe di attenzione) parameter that influences bridge management activities (such as interventions, structural monitoring, preliminary or in-depth assessments of structural safety, etc.) [16]. By considering the bridge data collected by means of the LGP Annexes, it is possible to record and process them to obtain information on risk, intervention priority, in-depth structural safety assessments, and condition status.

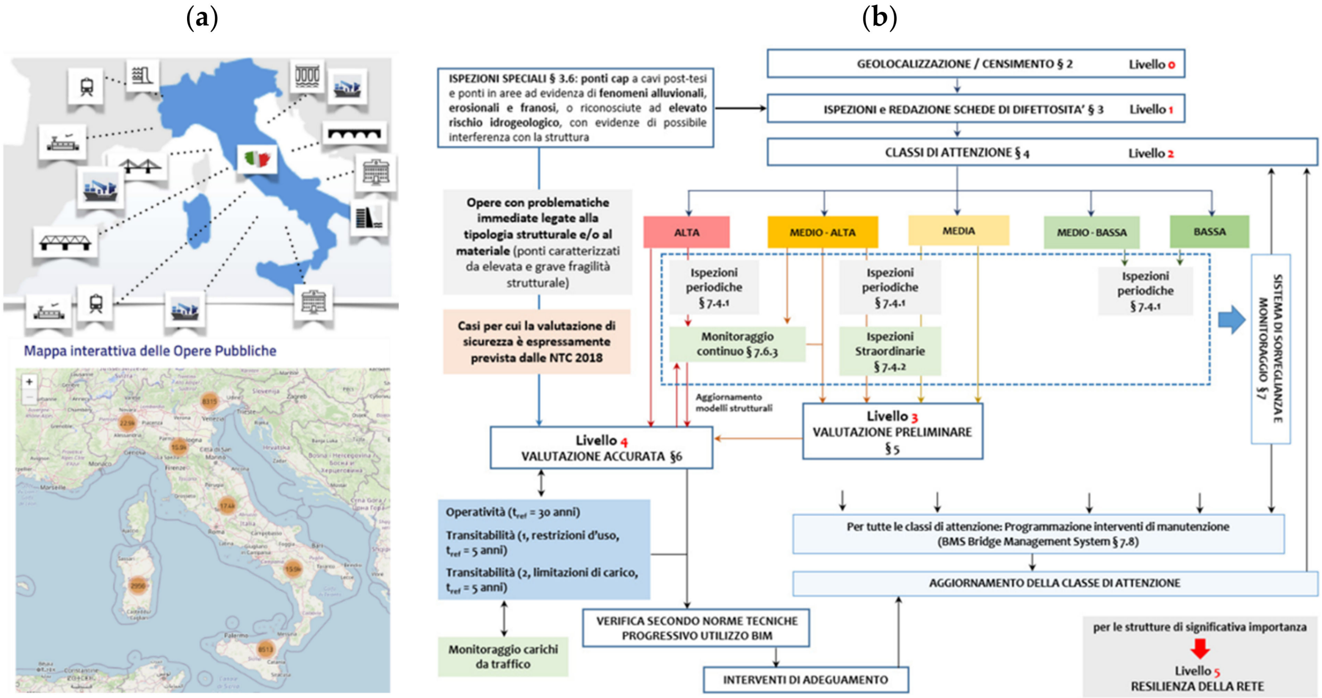

Figure 1. The AINOP platform and relative interactive map of public works (**a**); multilevel approach and related analysis levels according to the LGP (**b**).

Taking a new perspective on the management of civil works in BIM, in Europe, directive 2014/24/EU suggests introducing BIM methodologies in the field of public procurement. Italy has implemented this directive (by means of Legislative Decree No. 50 of 2016), allowing the authorities to request the use of such methods and digital tools. Subsequently, in 2017, Ministerial Decree No. 560 of 2017 was issued. This introduced the procedures and times for the gradual introduction of BIM methodologies for the modeling and management of information, regarding buildings and infrastructural assets in public works, in addition to the concept of interoperability as performed by means of non-proprietary open formats and platforms. In August 2021, Ministerial Decree No. 312 was issued with the aims of implementing a series of new measures for the use of the BIM, introducing further changes to the previous decree, and identifying the reward criteria for the use of BIM. Additionally, the LGP address the integration of existing systems in service so far (e.g., BMS, ERP) with BIM methodologies. All this should be included in an overall framework of information management, which aims to ensure the appropriate safety level of the national infrastructure assets, based on the progressive adoption of information with related objects, common data environments, and interoperable platforms of data.

1.2. Problem Statement, Proposal Aim and Structure

As also emerges from the analysis of the regulatory context, there is a need to digitalize the management of existing bridges, with the aim of not only creating BIM information models but also of enabling new ways to process and manage information relating to the definition of structural safety, risk, and priority intervention. Currently, such information is not yet managed through a BIM-based approach. Additionally, the existing systems used today by managing bodies or authorities are still not ready and organized to fully meet the new requirements. Indeed, there is a lack of any all-encompassing BIM-based solution to manage the required information in accordance with recent Italian regulations. To achieve that, a new digital organization of context-related information—a recent approach introduced by the ISO 19650 series [17] and the UNI EN 17412-1 [18] by means of the definition of the Level of Information Need (LoIN)—was put forward. The authors, starting from the definition of the specific LoINs, propose a digital framework (i.e., RCBFramework) enabled by dedicated scripts and algorithms, developed in a programming application, and subsequently integrated into the BIM environment. This framework has been developed for a specific type of road bridge (namely, reinforced concrete girder bridges), but given its approach, particularly from an IT perspective, it could in future be extended to apply to other types of bridge or viaduct. Moreover, the proposed solution is enabled by the development of a specific input environment in which all necessary information is provided. By processing the inputted data via custom-designed scripts and algorithms implemented in visual programming (VP) and authoring environments, BIM models with synthesized information regarding risk, intervention priorities and structural safety were created and then managed in a collaborative environment. The use of a specific collaboration platform allows us to organize a collaborative work involving various technicians and support the information management organized according to the adopted LoIN approach. In conclusion, the proposed digital strategy was subsequently applied to two case studies in order to test the capabilities and effectiveness of the proposed approach in the analyzed regulatory context.

As regards the organization of this article, Section 1 provides an introduction for the context under investigation. The rest of the paper is organized as follows: Section 2 provides an overview of the application of BIM methodologies in the management of existing bridges. Section 3 deals with the organization of the BIM-based solution we propose, including the development of the digital framework and the strategy for the information management activities. Section 4, meanwhile, highlights the implementation of the proposed solution and the results obtained for the selected case studies. Section 5 then gives a final discussion of our results, and Section 6 presents our final conclusions.

2. Overview of the Application of BIM Methodologies in the Management of Existing Bridges

2.1. Analysis of the BIM Context for the Authors' Proposal

Building information modeling has been defined by the National BIM Standard as "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward". The information that is generated and exchanged by means proprietary formats obviously guides the user towards specific solutions. Meanwhile, in openBIM, digital solutions developed with several open standards in mind—such as Industry Foundation Classes (IFC), Model View Definition (MVD), Information Delivery Manual (IDM), and so on—can enable and support the open exchange of information among all the professionals involved on a project [10,19–30]. However, the definition of BIM models should be carried out according to the widespread 'use case' concept, which establishes a common language for BIM applications throughout all lifecycle phases. In the case of the scenario under investigation, some uses cases, such as record modeling (RM), asset management (AM), and maintenance and repair information (MRI), may be considered. On the other hand, as regards the details of the BIM model itself, reference can be made to specific "Model Uses" [9]. These help identify the kind of information that is required, delivered, or integrated into the BIM models. In the context under analysis, it can refer to model uses such as "Algorithmic Modeling", above all regarding geometry generation, as well as "Building Inspection" and "Asset Maintenance", for a more thorough assessment of information and documentary aspects in the management context of a civil asset. In order to define what information is needed for BIM modelling and information management activities, alphanumeric and documental information relating to O&M activities predominates over geometric information, and these are fundamental to ensure the control of the condition status and bridge performance over time [3,5,11,21,31]. Regarding the management of a civil infrastructure, specifically in the case of bridges, several studies [9,11,32,33] consider the level of development (LOD) approach for their developments and proposals. The widespread application of such an approach has led to the development of some differences between LOD standards in the different countries [34]. In addition to this existing LOD concept, a new approach has been proposed by the ISO 19650 series, i.e., level of information need (LoIN) [17,18]. The new framework is different from LOD; indeed, with this new approach, it is possible to: (i) improve the information quality; (ii) reduce the risk of errors about the interpretation of requirements and control of compliance with contractual requests; and (iii) improve the process effectiveness, producing only the most necessary information, thereby avoiding waste, surplus, or a lack of information. This concept, accordingly, was subsequently defined in a recent standard, UNI EN 17412-1 [18], which has also been adopted in Italy, introducing the relevant aspects (at the geometric, informative, and documentary level) for the creation of the information needed to define a digital model. Given that this approach was recently issued, there is still a lack of specification and related applications to real scenarios, including the case of bridge management. For this reason, the authors have proposed a LoIN setting for bridge management in the cases under investigation.

2.2. BIM Methodologies Integrated with Other Technologies

In the AECO sector, for the creation of a civil infrastructure model, there are many software vendors and their software solutions. This software can be used for creating CIM models or performing simulations and analyses in different domains (transportation, structures, water, energy, etc.). In addition, some vendors also provide APIs (application program interface) and SDKs (software development toolkits) for customizing their tools. In the field of civil infrastructure, some applications (BIM-authoring or other software) can be used for different uses [11,28,32,35–38]. Usually, these are referred to some vendors such as Autodesk (e.g., Revit, AutoCAD, Civil 3D, InfraWorks, Structural Bridge Design, Navisworks, etc.), Bentley (e.g., MicroStation, ProjectWise, RM Bridge, Power Rail Track, Power InRoads, etc.), CSI (e.g., SAP200, CSiBridge), Tekla (e.g., Tekla Structures, Tekla Bimsight), Graphisoft (e.g., ArchiCAD), and so on, in addition to visual programming tools (e.g., Dynamo or Grasshopper) that can support activities related to the BIM-authoring applications. Therefore, the possibility of using VP tools (e.g., Dynamo, Grasshopper, etc.) permits automated or semi-automated operations for the development of solutions for model building and information management [28,39–42]. In the design phase of a bridge, these tools can be efficiently used for the development of different scripts for the generation of BrIM models, demonstrating a consistent reduction in modeling times [36]. In the specific context of bridge management, some information (e.g., relating to inspections) can be managed by developing structured workflows and scripts created in VP environments, starting from input data in an organized and structured way [11]. In the infrastructure field, BIM can be successfully applied to the design phases of infrastructure such as railways [36,40,42–44]. As also for buildings, in the context of bridges, these methodologies can be applied to the management of risk-related information [24,45–49]. BIM can also be used for the digitalization of existing bridges in addition to support the registration and maintenance of relevant information, both historical and current through the use of databases connected to the digital model [11,14,21,27,31,36,49–52]. BIM methodologies can be assisted and integrated with by other technologies as well. For instance, Internet of Things (IOT) technology could be considered in order to support smart structural evaluations and develop "intelligent" management of a bridge's lifecycle [49,53,54] also combined with other means such as IFC [49,54–57]. Furthermore, specific tools, namely bridge management systems (BMS), can also provide decision support for the entire lifecycle of a bridge. In this direction, several studies [2,8,9,24,25,50,58] consider a possible integration between BMS, BIM methodologies, and other technologies as well, such as advanced computing and imaging techniques, with the aim of improving reliability and efficiency in bridge management [2,52,59,60]. As far as existing bridges are concerned, complete digitalization is necessary with the goal of supporting the management and maintenance of specific characteristics over time. This digital reconstruction can be put into action with automatic or semi-automatic methodologies that use survey data (e.g., point clouds) to generate models, for example, in IFC format, or for the automatic detection of the bridge elements and related damage information [21,59,61–64]. In addition, between BIM and FEM, the adoption of an adequate parametric strategy allows one to manage highly complex projects and facilitates collaborations between different disciplines or technicians [65–67]. BIM models, built in accordance with specific O&M requirements, can enable the extraction and exchange of data directly with existing asset management systems [68]. Digital management can also be supported by other solutions, such as collaborative platforms. These enable a common data environment (CDE) to be structured and organized according to national (i.e., the UNI 11337 series, in Italy) or international (e.g., the ISO 19650 series) standards. Several studies [4,10,69–72] prove the effectiveness of using CDE platforms, digital tools, or other systems to support the activities related to infrastructure including bridges. Moreover, an important aspect in the construction sector is interoperability, understood as the ability of two or more systems, networks, or applications to exchange information between themselves [73–77]. When BIM application have to be defined, interoperability issues and application compatibility logics in addition to their update times should be taken into account [7,77]. This can be performed through non-proprietary open formats such as IFC (ISO 16739-1), promoted by buildingSMART International (bSI). As has been demonstrated by various practical sources (e.g., Bridge Information Modeling Standardization by FHWA and the National BIM Guide for Owners by NIBS), some open standards, such as IFC and LandXML, are able to describe many aspects of a bridge throughout its lifecycle [20,24,54,78]. Obviously, the latest bSI projects (IfcBridge, IfcRail and so on) enable increasingly well-performing versions of the IFC standard capable of representing these assets both geometrically and semantically. In particular, the IfcBridge project [20], concerning IFC extension for bridges, has enabled the issue of a related version of the IFC schema (IFC4.2). Applications of visual programming could be considered to build and export bridge information models according to IFC4.2 release [28]. Although it is currently withdrawn, this has been considered in versions that are currently in development by bSI (e.g., IFC 4.3 or the latest IFC 4.4.0 version) for the infrastructural field. Indeed, in the O&M scenario for road infrastructure, IFC applications remain limited due to a lack of specific semantics [78]. At the same time, the openBIM approach can be considered for the management of all in-operation assets (including bridges) belonging to existing road or railway infrastructure [10,78].

Thus, according to the state of the art and what was stated in Section 1.1, there is a need to define an all-encompassing BIM-based approach for the management of existing bridges and to underline the lack of a specific BIM solution for the generation, processing and management of information related to a specific regulatory context. To date, information is still managed almost entirely at the level of asset management platforms, without a fully integration with collaborative BIM platforms and interoperable data models for an effective exchange of information and bridge management. The digital solution proposed by the authors processes and manages all the required information by means of specific workflows based on a developed framework, and through the use of a number of environments and technologies (programming environment, BIM-authoring software, Visual Programming solution and a BIM collaborative platform).

3. Development of a BIM-Based Solution to Manage Existing R.C. Bridges in the Context under Investigation

3.1. Organization and Objectives of the Proposal

The authors, by means of the proposal presented here, have defined an operational framework with which one can digitally manage a significant proportion of the bridges and viaducts that are part of the Italian infrastructural heritage, namely R.C. girder bridges. Our proposal enables us, via two real case studies selected because of their different characteristics, to demonstrate the capabilities of the proposed digital framework for generating diverse bridge configurations, managing and processing information related to the context under analysis. In this scenario, the solution was able to quickly generate BIM models starting from input data, such as plano-altimetric alignments and structural characteristics (number of piers, beams, etc.), through information entered in a custom-made input (developed in Excel). Specifically, the proposal considers girder bridges made of reinforced concrete (whether cast in situ or prefabricated), with bridge decks consisting of a grillage of beams (longitudinal and transversal beams), with any kind of longitudinal or transversal positioning, piers with single columns or multi-columns, and any kind of relative positioning between the piers or abutments and decks. The solution was developed with the aim of not only representing these bridges geometrically but also of enabling the management of information processed by means of scripts and algorithms, integrated into the visual programming environment, beginning with input data and relating to the condition and structural safety of the bridge under consideration. The use of a collaborative environment (i.e., usBIM.platform) was necessary to support the proposal based on the LoIN setting, where the bridge information model was considered as the center of digital workflows which involved various technical figures (e.g., structural engineers). These can take place in the common data environment built in accordance with the specific regulatory context (e.g., ISO 19650).

In conclusion, the following objectives were considered in developing the proposed solution: (i) development of a data input environment in addition to the organization of specific BIM objects following a LoIN setting; (ii) definition of an IT solution to be implemented in a BIM environment; (iii) development of specific procedures for the generation of BIM models, for the processing and updating of the information over time related to the required activities (census, survey, inspection, risk assessment, structural safety assessment, etc.); (iv) testing and implementation of the proposal on selected bridge cases.

3.2. Identification of Necessary Data and Definition of Information Strategy in the BIM Environment

A part of the proposal covered by this paper consists of the generation of BIM models, in accordance with specific information requirements based on geometrical, information and documentation setting. The required information was selected in accordance with the regulatory references under consideration (i.e., NTC, AINOP, and LGP). Analyzing different sources, the authors identified different levels of information: (i) a global level, which refers to information referring to the global bridge structure; and (ii) an element level, which refers to information relating to any structural bridge component (e.g., beams, columns). Accordingly, this information was organized in five layers depending on the regulatory source, as shown in Table 1.

Table 1. Definition of layers related to bridge information in the considered context.

Layers	LGP	AINOP	NTC
L0	✓	✓	
L1	✓		
L2	✓		
L3	✓		✓
L4	✓		✓

As far as the LGP is concerned, on the other hand, these are organized in a multilevel approach (see Figure 1). With reference to the proposed mode of organization (Table 1), Layer 0 is characterized by information referring to both the AINOP and LGP. As regards the AINOP, this refers to information requested and present in some forms (e.g., Technical Annex A of the LGP). Meanwhile, the LGP, for survey information, refer to the relevant form (e.g., Annex A of the LGP —Level 0 bridge survey forms). The information identified at this level aims to have no duplicates. Layer 1, on the other hand, refers only to the LGP and provides information about the inspections that are carried out using visual surveys and collected through relevant forms (Annexes B, C and D of the LGP). For instance, Type B Annexes require information distinguishing between the type of material (steel, prestressed or cast in situ concrete, masonry, etc.) and element or part of the structure (pier, deck, etc.). Furthermore, there is a catalog of defects (Annex C of the LGP), which, for each element or part under consideration (beam, arch, etc.), reports a series of characteristic parameters for each defect (e.g., severity of defect "G", extent of defect "k1", intensity of defect "k2") with relevant descriptions and an associated range of numerical values that can be assumed. Finally, in the case of particularly vulnerable elements, such as the reinforced concrete beams with post-tensioned cables, "special" inspections are required, and resulting information can be collected in a relevant form (Annex D of the LGP). Layer 2 deals with the classification of assets via the definition of the Class of Attention (CdA), both in relation to an overall value and according to individual risk (structural and foundational, seismic, landslide, hydraulic), in order to establish a priority for the in-depth analyses, structural checks as well as for the planning of necessary maintenance. Five attention classes are defined (high, medium-high, medium, medium-low, low). This parameter is defined by gathering data collected in previous levels. Layer 3, in the context of the LGP, involves preliminary assessment of structural safety starting from some preliminary CdA definition for the bridge in question (e.g., medium-high, medium). Layer 4, finally, refers to the in-depth structural safety assessment. In the context of the LGP, a thorough assessment of safety must be performed in some cases such as where the CdA is high or where specific instructions have been given derived from the previous level (Level 3). This layer consists of information relating to both the NTC and the related circular as well. With regard to the LGP, these establish the different levels of analysis for the bridge under consideration (complete adequacy, operability, transitability NTC 2018—type 1 and transitability CdS—type 2). Each state refers to precise requirements relating to the coefficients, for materials and actions, to be considered for the verification.

Given this information, the strategy took into account the final export of the bridge model in IFC format as well. If we consider this standard, semantic extension strategies can refer to two types of approaches: static (class definitions or related attributes) and dynamic (use of PSet/Properties or the proxy class concept) [44,46]. For this proposal, so far as alphanumeric information is concerned, reference was made to the second approach (development of PSets and related properties). Each identified layer is characterized by different sets of information organized in the BIM-authoring environment by means of the creation of parameters and associated, depending on the case, with either a structure or element level (see Tables 2–4). The subsequent IFC mapping procedure takes place by means of scripts, subsequently integrated into VP environments (e.g., Dynamo), which allow one to define the related configuration file automatically.

In addition, some information was conveyed through parameters that express summary information. For instance, with regard to structural safety, the Safety Factor parameter (considered as the ratio between capacity and demand) was used. Considering the property set SBM_L4_RCBeamStructuralVerification, shown in Table 4, the property BendingSF,min expresses the minimum coefficient for bending safety among all the sections considered for a structural element (beams, columns and so on). This approach is also considered for the other types of verification, and in general has been applied both at global (e.g., P-Δ, structure regularities, etc.) and elemental (e.g., shear, torsion, etc.) level.

Table 2. Layer-related information (i.e., PSets) for the BIM modeling and management activities in the Italian regulatory context.

Layer	IFC Class	PSet	Description
	IfcBuilding	SBM_L0_BridgeStatus	General information about the bridge's in-service status
		SBM_L0_Classification	Information regarding transport networks or waterways
		SBM_L0_ConsequenceClasses	Information about consequence classes
		SBM_L0_DesignDocuments	Project information (at different design levels) and maintenance documents
		SBM_L0_DL22012004	Information about DL n. 42 on 22 January 2004
		SBM_L0_GeneralInformation	Information about bridge (e.g., IOP Code, name, owner, etc.)
		SBM_L0_GeometricalData	Geometrical data and characteristics (e.g., spans, lengths, etc.)
		SBM_L0_HydrogeologicalRiskDocuments	Documents about hydrogeological risk
		SBM_L0_InspectionsMonitoringHystory	Information about the previous inspections and monitoring activities
		SBM_L0_Localization	Information about localization and seismic hazard
		SBM_L0_MaintenanceHystory	Information about previous maintenance plan and related operations
		SBM_L0_ProjectData	Information about the project (e.g., designers, project approvals, codes, etc.)
		SBM_L0_RoadNetwork	Information about road network and daily traffic levels
		SBM_L0_StructuralInformation	Information about structural characteristics (regarding elements, materials, etc.)
	IfcSite	SBM_L0_GeomorphologicalData	Information about the site morphology
1	IfcBuilding	SBM_L1_LastBridgeInspection	Information about last inspections through numerical values (e.g., DR)
		SBM_L1_StructuralSketchforLastInspection	Information about last inspections through a link to drawings, photos and other
	IfcSite	SBM_L1_LastGeotechnicalInspection	Information about last geotechnical inspection
		SBM_L1_LandslideRisk	Information about the landslide risk (state of activity, type, etc.)
		SBM_L1_HydraulicRiskGeneralInformation	General Information about hydraulic risk
		SBM_L1_HydraulicOverflowRisk	Specific information about hydraulic overflow risk
		SBM_L1_HydraulicErosionRisk	Specific information about hydraulic erosion risk
2	IfcBuilding	SBM_L2_CdABridgeInformation	Information about the CdA values as a result of the implemented approach
	IfcElement	SBM_L2_ElementInformation	Information about condition status related to each structural element
3	IfcBuilding	SBM_L3_BridgePreliminaryCheck	Bridge structure information regarding a "preliminary" structural verification
	IfcElement	SBM_L3_ElementPreliminaryCheck	Structural element information regarding a "preliminary" structural verification
4	IfcBuilding	SBM_L4_BridgeStructuralVerification	Bridge structure information about an "accurate" structural verification
	IfcElement	SBM_L4_RCBeamStructuralVerification	Structural element information regarding an "accurate" structural verification
		SBM_L4_RCColumnStructuralVerification	
		SBM_L4_RCWallStructuralVerification	
		SBM_L4_RCFoundationStructuralVerification	
		SBM_L4_RCSlabStructuralVerification	

Table 3. Example of information regarding a particular 2nd Layer PropertySet (i.e., SBM_L2_CdABridgeInformation).

Property Set	Property Name	Value	Meaning
SBM_L2_CdABridge Information	CdA	Text	CdA overall value for the considered bridge
	CdAStructuralAndFoundationalRisk	Text	CdA value regarding the considered risk (Structural and Foundational Risk)
	CdASeismicRisk	Text	CdA value regarding the considered risk (Seismic Risk)
	CdALandslidesRisk	Text	CdA value regarding considered risk (Landslide Risk)
	CdAHydraulicRisk	Text	CdA value regarding considered risk (Hydraulic Risk)
	RelativeDefectiveness	Real	Information about condition of the bridge and its structural elements
	CdAReport	Text	Information about CdA report
	LastOrdinaryInspectionDate	Text	Date of the last ordinary inspection
	OrdinaryInspectionsFrequency	Text	Frequency regarding ordinary inspections activities
	LastExtraordinaryInspectionDate	Text	Date of the last extraordinary inspection
	ExtraordinaryInspectionsFrequency	Text	Frequency regarding extraordinary inspections activities
	LastSpecialInspectionDate	Text	Date of the last special inspections

Table 4. Example of information regarding a specific Property Set (i.e., SBM_L4_RCBeamStructural Verification) related to the 4th Layer for a generic R.C. beam.

Property Set	Property Name	Value	Meaning
SBM_L4_RCBeamStructural Verification	BendingSF,min	Real	Minimum Safety Factor (Bending Moment) among all sections of the considered element.
	ShearSF,min	Real	Minimum Safety Factor (Shear) among all sections of the considered element.
	TorsionSF,min	Real	Minimum Safety Factor (Torsion) among all sections of the considered element.
	Zita,e,min	Real	The ratio between the maximum value due to seismic load, carried by the considered structural element, and the related value considered in the design of new construction.
	Zita,v,min	Real	The ratio between the maximum value due to variable vertical load, carried by the considered structural element, and the related value used in the design of new construction.

3.2.1. Definition of the Proper LoIN in the Context Being Analyzed

Taking into account what has been stated in the previous sections, there is a need to specify information requirements for the creation and management of BIM models in accordance with the scenario considered by the authors' proposal. The new approach related to the UNI EN 17412-1 standard provides a precise method for the definition of the level of information need by identifying: purpose (why), milestones (when), actors involved (who), and objects of exchange (what). In this respect, information should be organized according to geometric, alphanumeric, and documental aspects. The adoption of this new approach is justified by the fact that it is needed to manage all the information that is strictly necessary for a specific use and related purposes.

In this regard, Table 5 clarifies and summarizes, in detail, the LoIN considered with reference to geometric, informational, and documental information consistent with the purpose and phases that were identified. The first thing to be analyzed was the purpose. Record information, managing risk, and checking and monitoring of the structural safety were considered. Another aspect consisted in the identification of the lifecycle phase. Information models may refer to the O&M phases including any structural sub-phases (e.g., structural safety assessment, retrofit interventions, etc.). Actors, instead, refer to the specific structural activity being considered in the scenario under investigation (e.g., bridge structural engineer, bridge inspector, and so on). Following this new approach, the authors propose LoINs for the single component, global structure, and other aspects (such as site, project, etc.). According to the UNI EN 17412 Annex (e.g., type B), a suggested form was considered in order to specify and list the necessary information requirements. Below, an instance of a LoIN for a bridge element is shown.

Table 5. Example of proposed LoIN for the bridge component (e.g., beam).

Information Delivery Milestone	Operation and Maintenance Phases
Purpose	**Record information, managing risk, checking and monitoring of the structural safety**
Actor	**Structural Engineer**
- **Object**	"Beam"
- **Geometrical Information**	Requested
- Detail	Simplified representation
- Dimensionality	3D
- Location	Absolute
- Appearance	Digital
- Parametric behaviour	Not Requested
- **Alphanumerical information**	Requested
- Identification	Alphanumerical code
- Information content	SBM_L2_ElementInformation SBM_L3_ElementPreliminaryCheck SBM_L4_RCBeamStructuralVerification
- **Documentation**	Requested
- **Set of documents**	Sketches, drawings, documents, reports, photos (e.g., regarding condition status), etc.

In the case of the bridges considered in this proposal (i.e., reinforced concrete bridges), the 'simplified representation' of the bridge elements (beam, column, etc.) was chosen. This considers the modelling of the reinforced concrete part only, without the reinforcement. As regards alphanumeric information, this refers to the proposed parameters and related PSets (see Tables 2–4), which manage information derived from the census, inspection, structural assessment, and so on. In some cases (e.g., CdA), alphanumeric information is also obtained by processing other data (via scripts or algorithms belonging to the proposed RCBFramework) inserted in the input environments developed for the specific application. As regards documentation, these refer to information (e.g., images or sketches, photos, technical drawings, forms, schedules, structural reports, etc.) related to the activities pertaining to the structural bridge management.

3.3. Definition of a Digital Strategy for the Structural Management of Bridges in a BIM Environment

Since there is a clear need for automatic support for the creation and management of digital models and related information, the authors have developed a BIM-based solution (the RCBFramework) and a digital strategy, as described in Figure 2, which supports the following activities: (i) data entry (based on specific BIM objects and the data input environment); (ii) 3D model generation; (iii) model information management; and (iv) asset information management.

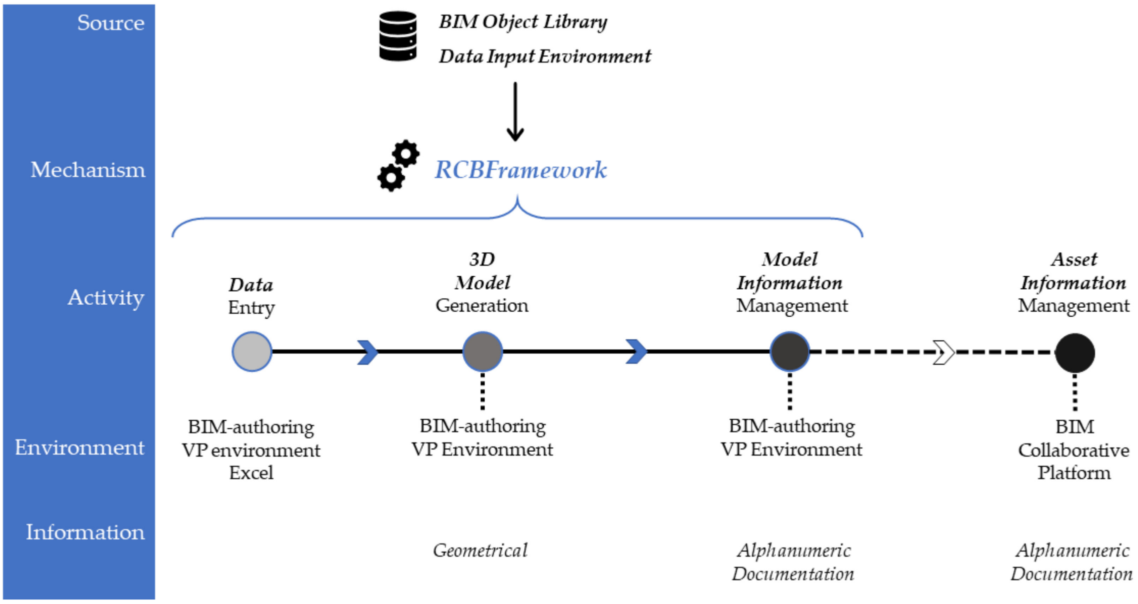

Figure 2. Proposed strategy to manage structural bridge information in the context under analysis.

In some cases, the IT frameworks were built through the collection of classes, which provided the implementation lines for the application being developed [79]. The structure of proposed framework was supported by scripts and algorithms written in the CPython and IronPython programming languages, frequently used and integrated into visual programming environments. The architecture of the proposed RCBFramework follows the well-known MVC pattern. This pattern, used in programming, organizes code into blocks (i.e., Model, View, and Controller) in order to keep them distinct and ensure the code's maintainability. The adoption of an advanced IT approach makes it possible to generalize the solution developed by the authors, in terms of IT model, both for the generation of the BIM object and for the information management, so that it is implementable in other kinds of BIM authoring environment. The following framework was structured according to classes and modules with different levels of abstraction or specialization. Therefore, following an object-oriented programming (OOP) approach, the code is organized into IT classes, which define a means to represent categories of objects (beam, column, etc.), with several attributes, which define the characteristics of the category of objects being represented (identification, dimensions, etc.). IT classes are supported by the inheritance mechanism, which can be significant when code reuse strategies are applied. In addition, several methods are set in order to support CRUD ("Create", "Read or Retrieve", "Update", and "Delete") operations related to specific data in relation to the various components of a bridge. For example, the "retrieve" methods permit us rapid editing operations of the geometry and information associated with some BIM objects. This framework organization was developed with the aim of being extendable to other types of bridges as well. Indeed, to achieve such extension, it will be necessary simply to develop new packages, modules, classes, and methods related to other kinds of bridges and their associated functionalities. Figure 3 describes the authors' activities for the development of proposed digital solution.

These were considered with the aim to test the proposed solution on the selected real cases of R.C. bridges.

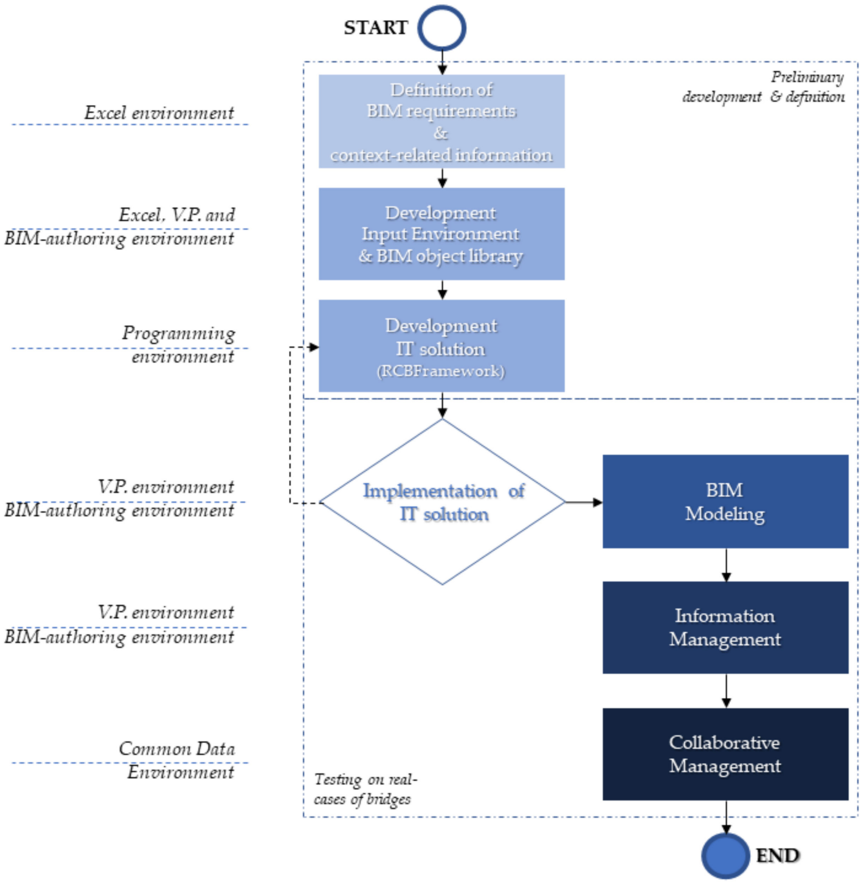

Figure 3. Activities and workflow related to the development of the proposed solution.

Figures 2 and 3 present a series of environments and applications. BIM-authoring software of Autodesk, i.e., Revit, mainly using Dynamo as an integrated VP environment have been considered. In addition, the Excel application has been chosen for organizing data flows with the Dynamo environment. These data will be necessary for creating and updating BIM model information. This environment gives us the possibility of implementing developed scripts, communicating with Revit through its API solutions. The proposed solution largely involves the definition of custom nodes that integrate scripts developed in the IronPython language. Finally, the implementation of the IT framework (i.e., RCBFramework)—in the BIM environment—required some time for building of a tailor-made solution (by means of methods and their scripts) that considers the peculiarities and characteristics of the bridges under analysis. However, this approach could be improved and extended in the future (e.g., through the development of other scripts and procedures) to consider other types of works.

3.3.1. Data Entry Input and BIM Object Library Setting

As a starting point, the authors developed a specific BIM object library and a data entry environment, which supported the model generation and information management activities in the analyzed context. In this environment, data were inputted, arranged in specific tables, and then collected in organized lists to be retrieved later and used by the proposed framework implemented in Dynamo (e.g., DAO modules). Information, for instance, derived from surveys or inspection activities, was entered through an input interface, sometimes also by means of macros developed ad hoc. These data were successively retrieved by scripts, implemented in the VP environment, and recorded in the specific parameters set in the BIM-authoring environment.

In accordance with the information requirements defined in Section 3.2, a BIM object library was developed. This was carried out considering the use of BIM-authoring software (i.e., Revit). Thus, a library of BIM objects (i.e., Revit families) was set, each related to typological elements pertaining to the bridges under analysis, specifically developing further families that are able to represent the specific features of the structural components belonging to the bridges in question. This approach enables the reuse of such components for the digitalization of other bridges with similar characteristics (e.g., bridges belonging to the same transport network) or extension in the future, with the addition of other Revit families, to other bridge typologies that are not considered in this proposal. For the generation of the geometry, information acquired by the surveys, existing drawings, and original documents were taken into account. These objects were considered as a starting point to be called up by the proposed framework, in addition to alignment information, for the definition of the bridge information model. Therefore, to move towards the automation of modelling procedures, the generation of BIM objects was carried out through the proposed 'RCBframework', implemented in the integrated VP environment, and the APIs made available by the authoring environment.

3.3.2. 3D Model Generation

As far as construction is concerned, a bridge is always built from the bottom up, i.e., proceeding from the foundations to the deck, and then on to the construction of the road or railway. In BIM modeling of a bridge, however, beginning with the infrastructure alignment, the construction of the model proceeds from top to bottom. The proposed framework, for the generation of the geometric part of BIM models, considers the concept of alignment (e.g., 3D polyline) as one of the input data sources in order to organize, arrange and create the structure of the bridge and its components, each of which is relatively positioned (in terms of angles, distances, etc.). The generation of the bridge, by means of the alignment data and other information (number of spans, number of piers, etc.) inserted through a specific input environment (e.g., Excel forms) allows us to automate the generation of the model and some of the information associated with it. This saves time compared to standard manual modeling procedures in BIM-authoring environments.

However, the approach defined by the framework needs to be contextualized in the authoring environment that is used, and with respect to the availability of related APIs. For this reason, classes and methods allow for implementation via dedicated developments in each environment under consideration (e.g., Dynamo, Grasshopper, etc.). In the authors' proposal, implementation of the RCBFramewok was realized in the Dynamo environment. This required the development of classes and methods, starting from the RCBFramework (e.g., in terms of classes and methods), with the subsequent definition of the related IT objects. The implementation of these procedures allows the production of BIM models, in the BIM-authoring environment, after being exported in IFC format by means of the implementation of other specific procedures. These, along with the selected information, were subsequently ready to be managed in the BIM collaboration platform.

3.3.3. Model Information Management

The information management implied by the framework we propose, which is consistent with the relevant regulatory framework, has the objective of developing a data model aimed at integrating the BIM models that originate from the generation solution described above. This data model was also built taking into consideration the structure of the IFC open format and what was reported in Tables 2–4. Accordingly, it was divided into five layers, each of which contains a reference to the IFC class and associated property groups. With reference to the previously described IT approach, in the case of information management, some attributes (e.g., ordinaryForms, specialForms, PsetForms, etc.) for specific classes (e.g., LongBeam class) were provided with the aim of associating, for instance, the information that derives from the inspection forms (e.g., ordinary, special, etc.) to the parameters and properties that were processed. According to the organization proposed previously, it is possible to write, to record and to extract data relating to the various inspections that take place over time. Therefore, the proposed framework contains the fundamental logic for the development of any changes regarding information management, for instance via CRUD operations we defined (e.g., in specific modules) for the expected information related to the elements that make up the bridge. Indeed, for each layer, the relative module was defined (e.g., base_im_L0_control.py for layer 0). Layers following layer 1 (e.g., from layer 2 to layer 4) were characterized by additional instructions for processing synthetic information regarding, for instance, the condition of a structural element (e.g., relative defects) or related to structural safety (e.g., structural verifications). Additionally, through the development of different methods, some reports are automatically developed (in .txt format) and referenced to the BIM objects of interest through specific parameters (e.g., considering URL data type). The purpose of a report is to make available bridge data, in a more useful and synthetic manner, via specific parameters (e.g., percentage variation over time of the relative defect parameters, such as k1, k2, and I, according to LGP setting). Therefore, once the BIM model was developed, from both a geometric and informational point of view, a method related to the IFC export settings of the BIM model was created as well. This enables the correct writing of the configuration file (given the specific BIM-authoring software, e.g., Revit) for IFC mapping operations in relation to the structure of the IFC standard in question. Thus, the procedures defined in the solution following the RCBFramework implement the logics for updating BIM models of bridges from an information point of view, where model information can be updated (via CRUD operations we defined) following the latest inspections that have been carried out. This proposal allows the digital model to be updated following inspections and the automatic tracking of the evolution regarding the conditions of the bridge and its structural elements, as well as the management of information related to the assessment of structural safety via synthetic parameters (e.g., safety factors).

3.3.4. Asset Information Management

Having introduced the part of digital strategy adopted for the creation and management of BIM models at both geometric and information levels, it is also necessary to manage the documental level belonging to the LoIN settings identified in Section 3.2 for the context under investigation. Indeed, LGP suggests the adoption of collaboration platforms and data sharing environments for the effective and transparent management of a given asset. In accordance with international (e.g., the ISO19650 series) or national (the UNI11337 series, Ministerial Decrees, and further updates) regulation context in force concerning BIM, it is possible to use "interoperable platforms by means of non-proprietary open formats" with data "that can be requested at any stage and by any actor", with information flows (relating to contracting authorities and related procedures) to be carried out "within a data sharing environment, where the digital management of information processes takes place" in addition to a series of requirements such as accessibility of roles-based figures, traceability of operations, support of various types of formats, and so on. Following this suggested direction, a specific BIM management platform has to be considered. This platform should also support digital workflows, involving various professional figures in a single collaborative environment. Thus, this kind of digital management allows the model to be interpreted as an "access key" reference, where information is always available and accessible to the professionals involved (structural engineers, maintenance technicians, bridge inspectors, etc.), which can manage and update the information about the bridge according to various structural contexts (structural safety assessment, maintenance operations, inspections, etc.).

4. Results

This section aims to describe the results obtained following the implementation of the proposal, providing a digital strategy suitable for application in the Italian regulatory context. The results have been achieved with reference to two real cases of reinforced concrete girder bridges. The expected results, in this case for R.C. girder bridges, include: (i) the generation of BrIMs according to proposed LoINs; (ii) implementation of the proposed solution for processing and managing relevant information in the context under investigation; and (iii) organization and management of structural information and related collaborative workflows. The first two results were achieved by means of the specific developed framework (RCBFramework), in addition to the availability of specific BIM objects and a data input environment. The third result is accomplished through the use of a collaborative environment and its related features.

4.1. Description of the Case Studies

The applicability of the proposal developed in this paper is tested on two judiciously chosen real-life cases with different characteristics. Two girder bridges were managed with our approach: a road viaduct and a motorway bridge, both made of reinforced concrete (see Figure 4).

(**a**) (**b**)

Figure 4. (**a**) Real case of road viaduct; (**b**) real case of motorway bridge.

The road viaduct (see Figure 4a) was built in the second half of the 1980s. It consists of a total of 34 m spans, giving a total length of about 1200 m. The spans are characterized by a transversal section with a total width of 11.30 m. The decks are made of four prefabricated post-tensioned R.C. beams, arranged with an interaxis distance of around 2.8 m, connected on site with five transverse beams and a slab of cast-in situ reinforced concrete. The piers are made of a single circular column of reinforced concrete and, on top, a beam with a support system consisting of several R.C. blocks. The second case study (see Figure 4b) involves a motorway bridge, built in the early 1960s and made of three simply supported bridge spans. The decks are 24 m wide and made with a grillage of transverse and longitudinal beams. Each span is characterized by 10 longitudinal beams of R.C. cast in situ with an interaxis distance of around 2.4 m. The two side bridge spans are 8.84 m long and include three transversal beams, while the central span is 18.62 m long and includes four transversal beams. The decks, piers, and abutments are all made of reinforced concrete cast in situ. The three spans also have non-rectangular decks with a deviation angle of around 44 degrees. Support devices consisting of lead plates of various sizes are placed on top of piers and abutments. The piers consist of rectangular section columns in the central part and polygonal section columns in the end parts of each bridge pier. These cases were also selected in order to test the capabilities of the proposed framework in generating BrIMs for different configurations of bridge structure, with reference to the different geometries of the constituent elements and the arrangement of the structural elements along the bridge's alignment.

4.2. Implementation of the Proposal

Everything we have proposed was implemented by defining workflows that involved Excel, IronPython, Dynamo and Revit, along with use of the collaborative platform. Excel software was used as an environment for the management of input data through the development of ad hoc input interfaces, both for BrIM generation and information management. Dynamo, meanwhile, was used as an environment for the implementation of the scripts and algorithms that was developed in the programming environment (as shown in Figure 5 below).

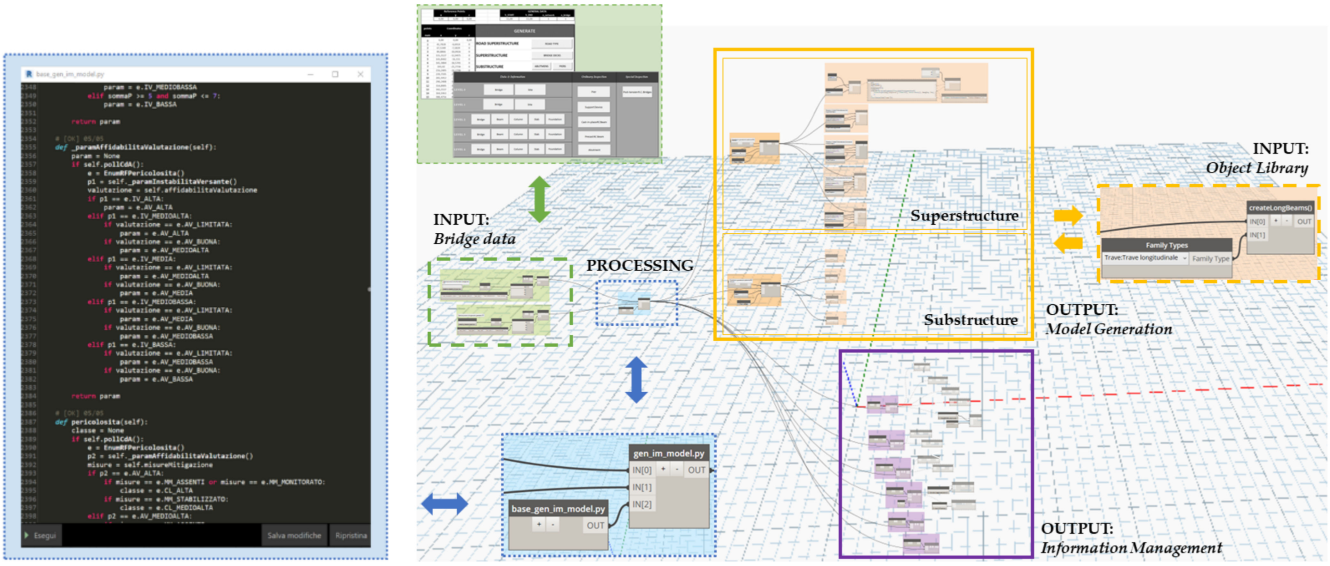

Figure 5. Dynamo architecture for supporting the proposed solution with regard to model generation and information management activities.

Dynamo and Python interacted via the "Python Script" node, where the code can be written using the Python language. This allowed us to implement, via scripts and algorithms in the Dynamo environment, the proposed IT structure that constitutes RCBFramework. In the Dynamo environment, starting from the provided classes by the framework, the necessary implementations for the case studies were developed within several "Python script" nodes (e.g., "ge_im_model.py", which includes more than 2000 lines of code referring both to the generation of models and the information management activities), as highlighted in the blue boxes of Figure 5. Retrieving data from inputs built in Excel, the solution implemented in Dynamo allowed us to instantiate the IT objects and to generate associated BIM objects with related information. Specifically, in the "Model Generation" box (in orange, see Figure 5), the use of the "Family Types" node was planned as an input to the method for the creation of a relative element (e.g., longitudinal structural beams). For each component of the bridge (beam, column, wall, etc.), a specific Revit family was developed (e.g., LongitudinalBeam.rfa) in accordance with the reference IT class for the bridge component in question (e.g., "LongBeam" class). This logic was applied to all the structural components of the bridge. These implementations use the available APIs, from both Dynamo and Revit, for supporting the generation of the bridge information model and the information management activities in the regulatory structural context under analysis. This logic was applied to all the structural components of the bridge.

4.2.1. BIM Model Generation

Starting from bridge alignment, along with specific settings for local reference systems and relative distances or slopes, the positioning of the bridge's structural elements was carried out both in the case of the alignments of the linear elements (e.g., beams) and the contours of bidimensional elements (e.g., slabs). This information was necessary to subsequently obtain the BIM objects. A similar reasoning was used for the piers, and related reference systems were also set for them. Furthermore, by processing the relationships and spacing between the various components of the considered bridge, the script allowed to obtain the correct positioning of the BIM objects, avoiding relative interpenetration. In the case of the piers, the positioning and generation of related BIM objects are linked to the deck information. The definition of BIM objects was carried out according to specific requirements (i.e., LOINs as shown in Section 3.2.1). Hence, the generation of the BIM model began with the generation of the structural bridge decks and their components, before moving on to the development of the piers and abutments—in other words, following a top-down system of modeling. Considering the modeling phase, in the case of both bridge superstructure and substructure, specific data (slopes, distances, etc.), provided during the input phase (e.g., though Excel forms), were considered by the developed framework. Starting from Dynamo instructions (see Figure 5), the generation of the BIM model, both for the road viaduct and motorway bridge, as shown, respectively, for Figure 6a,b, has been carried out. As may be noted in the following figure, the authors were able to reproduce the complete BIM model, consistent with the information provided in the input phase (alignment, bridge or element characteristics, and so on). In addition, in order to manage the complexity of non-rectangular decks, the attribute "beta" was added to the class related to the bridge pier, representing the angle formed between the axis of the pier itself and the longitudinal axis of the bridge deck being considered. This was then related to the alignment and relative position of the bridge's structural elements. Once the BIM models of the bridges were built, they were ready for the next phase of information management.

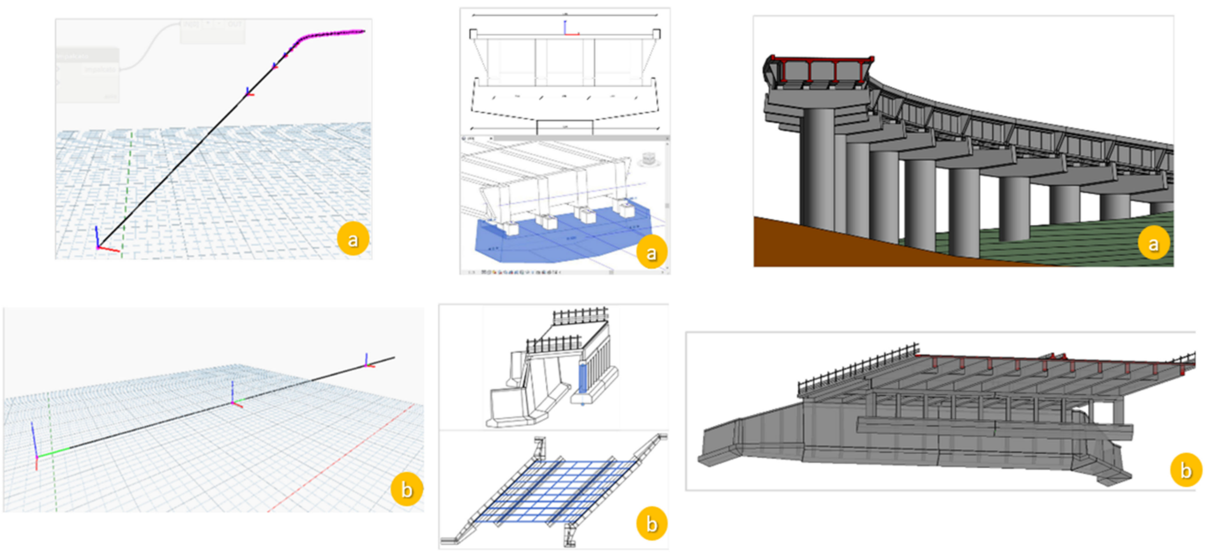

Figure 6. Generation of a BIM model by means of the proposed solution (Revit and Dynamo), for the road viaduct (**a**); and for the motorway bridge (**b**). Modeling phases consist of bridge alignment definition (1); BIM objects creation and relative position.

4.2.2. Information Management in the Context under Investigation

Following generation of the BIM models, the information that has to be managed regarding the bridge and its components refers to what was defined in Section 3.2. As explained in this section, the data model was organized according to proposed information layers (see Table 1). As shown in Figure 7, necessary data derived from original documents, surveys, inspection activities (with reference to the annexes considered by the regulations), and so on were entered through input interfaces (e.g., Excel macros), which saved the information in tables that were later retrieved by scripts. Subsequently, in the Revit environment, by means of certain instructions implemented in Dynamo, the creation of the parameters and their association with the reference Revit categories (e.g., Project Information, Structural Framing, etc.) were carried out.

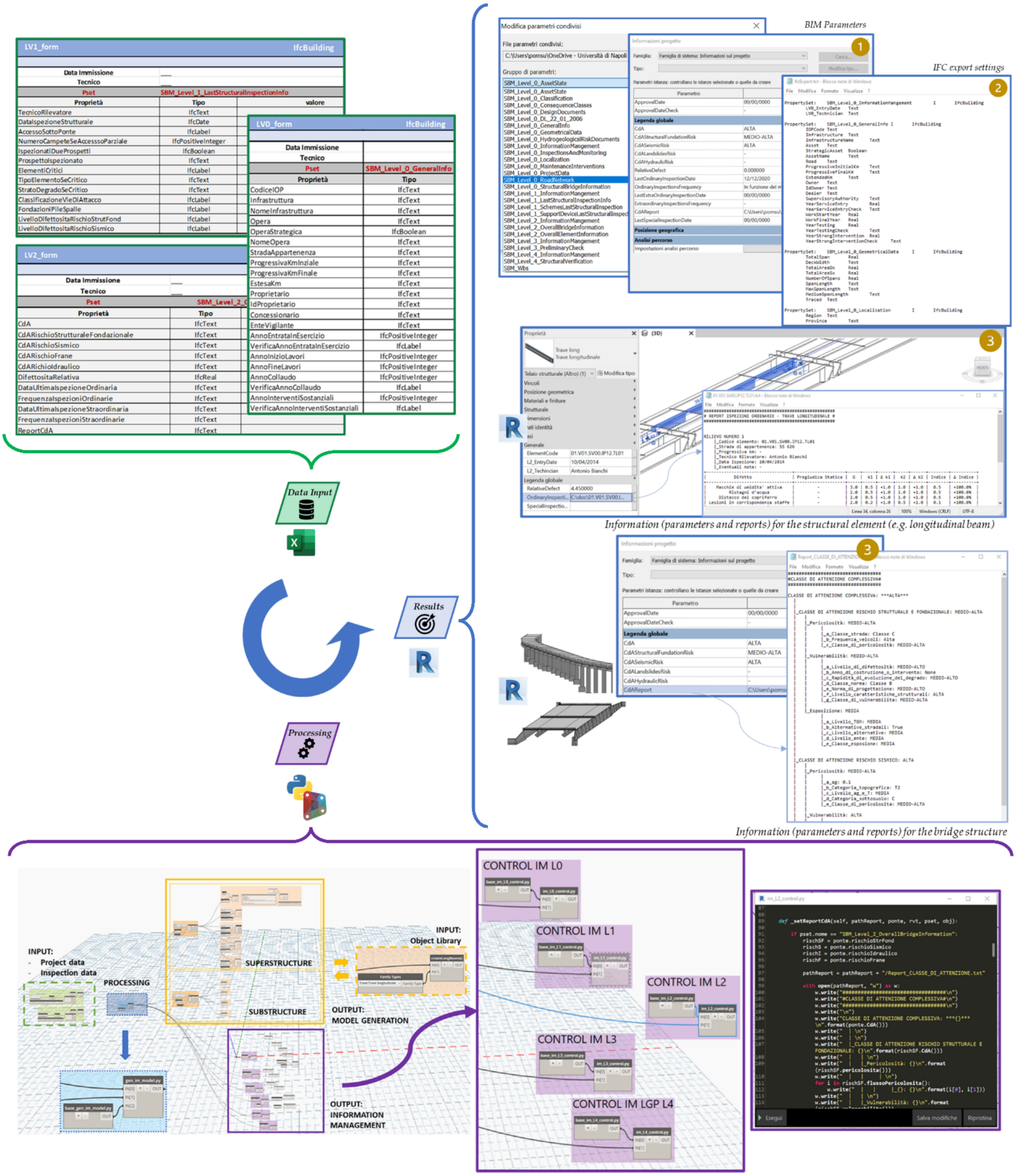

Figure 7. Organization of information layers in the BIM environment (Revit and Dynamo) for the definition of a specific workflow for saving, processing, and recording information, starting from acquired data. (1) Definition of BIM parameters and relative association to element categories; (2) definition of an automatic procedure for the exporting of IFC models; (3) association and updating of BIM parameters and summary reports both for structural component and bridge structure.

Considering what has been shown in Figure 7, some inputted data can be used not only for the enhancement of associated parameters but also for the processing of the summary information for the other information layers (e.g., the CdA parameter) in accordance with the logics derived from the context under investigation (e.g., LGP). As previously described in Section 3.3, the methodological approach we employ defines IT classes and related methods. For instance, in the case of the digitalization of CdA information, individual risks (structural and foundational risk, seismic risk, landslide risk and hydraulic risk), with related primary and secondary parameters, have been encoded. Accordingly, the CdA algorithm, after having processed and gained the related values, associated them to bridge structure as BIM parameters. To achieve this, the processing of the "Relative Defectiveness" value (DR) is necessary for the definition of the CdA values. As suggested by the LGP, DR is a numerical indicator of the condition status. This can be specified in reference to a single element, homogeneous groups of elements, or the whole bridge structure. On the basis of the defects that are encountered, which are described by filling in the relevant forms, through calculation of characteristic parameters (G, k1, k2, etc.), it is also possible to define the DR value obtained as Σi (Gi $\times$ k1,i $\times$ k2,i). Gi, k1,i and k2,i represent, respectively, the importance, intensity and magnitude of each defect detected during an inspection. These are defined on the basis of a specific catalogue of defects provided by LGP (as a specific Annex C of the LGP). Accordingly, the authors developed related scripts and algorithms, successively implemented in Dynamo, with the aim of making these operations available, with related output information, in a BIM environment as shown in the following figure. As shown in Figure 7, some reports were generated (in .txt format) through other scripts we implemented. For the single structural component of the bridge, this report was proposed for summarizing, for each inspection, data used in determining the DR value, with the aim of always having access to the relative defect history. As regards the bridge structure, another .txt file summarizes, for each inspection, data and values that were used in determining the CdA, for the overall value and for single risk values. Both in the case of single element or the bridge structure, this is automatically linked and recorded in the corresponding parameter (considering a URL-type value). All this was carried out with the aim of keeping BIM models constantly updated with the latest information, ensuring greater readability of the information obtained during processing. Additionally, this proposal allows the determination of the resulting information related to risk definition and structural safety for the bridge under consideration. As regards information layers L3 and L4, synthetic parameters (e.g., Safety Factor, as also proposed in Table 4) relating to bridge or element condition, obtained after structural assessments, were taken into account. This information was later associated within the informative model of the bridge as well. For all this target information (e.g., CdA, SFs, etc.), the implemented scripts in the Dynamo nodes, using data provided in the input phase, process it to obtain the specific information of interest (e.g., Tables 3 and 4) and then update the BIM model, associating the values thus obtained within the proposed parameters (e.g., through the updateLayer method). Accordingly, once data are available referring to the results of structural assessments (considering vertical loads, seismic actions, etc.), e.g., for a generic structural component, such as a longitudinal beam, obtained data can be referred to shear, bending moment, torsion, and other possible effects. This information refers to a certain level of analysis or verification (e.g., considering the LGP setting for a bridge status: Adequate, Operational, etc.), later specified in some parameters in the BIM environment (e.g., "StatusOfStructuralVerification","SBM_L4_BridgeStructuralVerification"). However, as a result of subsequent inspections or necessary monitoring activities, it is also possible to update these managed values over time. CRUD operations were prepared and implemented via the procedures integrated into the various Dynamo nodes. In addition, with the aim of managing the evolution of condition status related to the bridges being considered, some parameters, such as "relativeDefectivenessVariation", were defined as well. This is related to the relative defectiveness variation in question (for element, aggregation, or anything else in consideration) following consecutive inspections. It can be used to provide graphic views or to analyze related data for understanding the evolution of the bridge condition status. Following the evolution of a bridge's condition status, since the approach we propose can also track updates following inspection activities and structural assessments, in this context, the use of a collaborative platform (i.e., usBIM.platform) was also considered for the management of required information (according to the proposed LoINs), as shown in Figure 8.

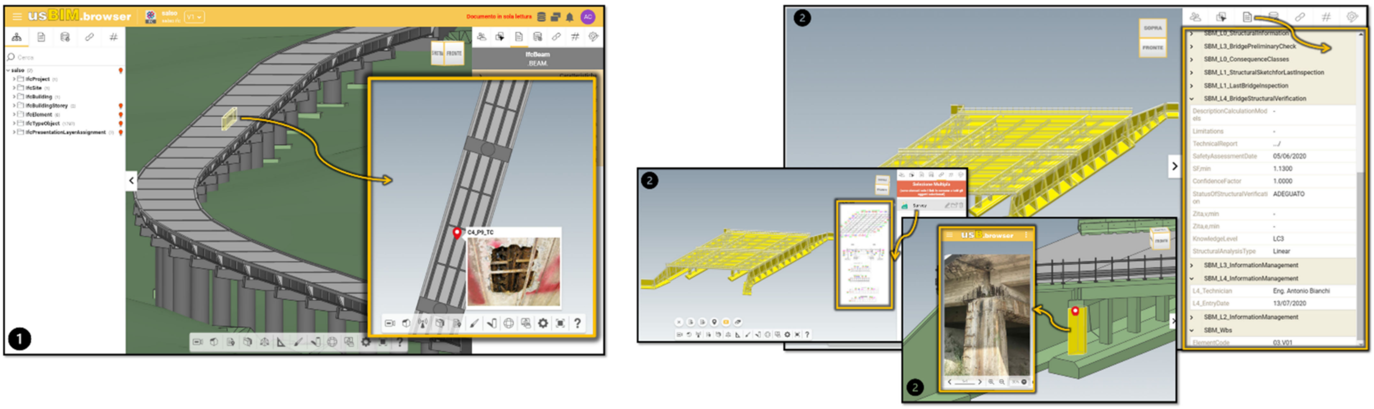

Figure 8. The management of information by using the collaborative platform (usBIM.platform) according to the proposed LoIN setting, both at global and local level, in the case of (1) the road viaduct and (2) the motorway bridge.

This environment consists of an IFC-certified platform (https://technical.buildingsmart.org/services/certification/ifc-certification-participants, accessed on 17 September 2022) and is characterized by several functionalities that can support bridge management activities. Therefore, BrIMs were loaded into this platform and conceived as the front end for reading and managing the information related to it.First of all, a Common Data Environment was organized in accordance with the relevant standards (UNI 11337, ISO 19650). Platform features allow us, for example, to define workflows for process control with advanced task management functions, procedures for reviewing or validating the associated information (e.g., gate function), and the integration of significant data by means of advanced functions for BIM data management. Another "link" function enabled the integrated management of the bridge data, allowing the association and storage of some of the documentary information collected during the various sub-processes that constitute the management phase (inspection, interventions, etc.). By considering these features, it was possible to record and associate documentation, specifically reports (relating to inspections, structural or geotechnical assessments, etc.), photos (relating to the overall condition of the structure or its individual component), manuals, documents, and other items regarding both bridge components and the total structure. The tools of the collaborative platform allowed us to exploit the information, through the model, by means of graphic filters, links, and images associated with BIM objects, thus facilitating their accessibility. This environment also made it possible to update the values of the defined properties (e.g., Tables 2–4) and enabled the management of the versioning of the models derived from the structural context in question.

5. Discussion

As analyzed in previous sections, there is an evident need to develop a new all-compassing approach based on BIM technologies for the management of bridges according to new requirements in the Italian regulatory context. Several studies [1,2,9,11,12,26,53,80–83] derived from the literature show examples of effective solutions to manage existing bridges; however, being related to different contexts, they are not suitable to meet the regulatory information requirements that arose from the analysis of the regulatory context in force in Italy today. With this in mind, it was necessary to develop an ad hoc solution to achieve the proposal goals defined by the authors. This solution, defined in the beginning both from an information (e.g., LoINs definition) and procedural (e.g., definition of an IT framework for the generation of BIM models and the information management activities) point of view, provides a feasible solution for managing one of the most widespread bridge typologies in Italy, i.e., existing R.C. girder bridges, meeting the requirements arising from the regulatory context under investigation. The contribution and scope of this proposal has been to provide a BIM solution with which one can manage structural information (regarding census, inspection, risk definition and structural safety activities) for bridges. Given the need for the management based on a BIM framework, derived also from the regulatory context (e.g., LGP) in a clear manner, the developed solution aims to define tailor-made BrIMs (in accordance with the proposed LoINs) along with their information management in the analysed context. These models represent an "access key" and a means for managing synthetic information sometimes processed in other systems (BMS, FEM, etc.). This proposal supports the definition of recurring workflows, regarding the data requests, to update external databases or digital platforms for the management of infrastructures (e.g., AINOP). Given its methodological approach, this solution can also be applied to other regulation settings, after having specified the required information and related logical flows to define them.

Following the proposal goals, as stated in Sections 3.1 and 4, a series of outcomes were achieved. Previously, the authors set customized LoINs, providing an organized reference for modelling and information management activities due to a lack of LoIN specifications in the context under investigation. Indeed, in the case of bridges, unlike the existing LOD approach [11,21,32,33,53], the LoIN approach establishes and optimizes the information that is strictly necessary, favoring saving resources. Accordingly, a BIM object library was developed related to the typological bridge elements considered, allowing the future reuse of such components for the digitization of other bridges with similar characteristics, or the extension, in future, towards other bridge typologies not considered by this proposal. In order to support the model generation and information management activities, a data entry environment was necessary to collect and organize, in specific tables, the data (e.g., derived from censuses, surveys, or inspection activities) to be subsequently retrieved by the proposed framework implemented in Dynamo. For this purpose, data were entered via ad hoc interfaces (e.g., macros in Excel) developed by the authors. Information management activities are therefore not limited to associating parameters with the BrIM model, but a sort of application that filters, processes, and synthesizes the required data in order to support the planned decision-making processes. In addition, the BIM model is constantly updated in terms of structural risk and safety information by means of proposed and customized solutions to the needs (e.g., CdA determination) dictated by the regulatory setting. Indeed, the authors, developing and implementing CRUD operations within the proposed digital solution, allow the construction, modification, and updating of the information regarding BrIMs. Through the methods and procedures we developed, the automatic processing of some information (e.g., reports linked to BIM models) was also conceived, with reference to both the overall structure of the bridge and its components in addition to the retrieval at any moment of various scenarios that have occurred over time (e.g., data related specific inspections). These allow possible comparisons aimed at more thorough appraisals of a bridge's condition and, therefore, suggestions for more appropriate and timely interventions. All this, therefore, has been possible by means the solution we propose, based on the module structure and IT pattern in question (i.e., MVC), which provides an organization that is simpler and easier to use, maintain, and improve in the future. Following the authors' proposal, the evolution of the condition status and the management of a bridge's structural safety were also supported by the use of a collaborative platform that was essential to manage and support the required LoIN setting. The validity of the proposal has been compared to what was previously only possible manually. For instance, by means of the regulatory procedures implemented via the developed scripts and algorithms, the same numerical results, related to what was previously obtained by the manual development of such procedures, were achieved. Applied to two real case studies, this proved a rapid development of modeling activities regarding the BrIMs related to various configurations (e.g., single or multicolumn piers, rectangular or non-rectangular decks, etc.), in addition to processing and managing the information required by the context under investigation. This organizing structure also allows us to automate, starting from a built input environment (e.g., through macros in Excel), the generation of a BrIM and the information exchange supported by open formats such as IFC. The related procedures are carried out in an automated manner by scripts and algorithms, which allows us to reduce times and errors when compared to the equivalent manual practices.

As regards the actual limitations of this work, these consist in the following: (i) the approach defined by our framework should be contextualized with respect to the specific BIM-authoring tool, VP environment, APIs, and programming integrations under consideration; (ii) the developed solution is capable of generating, processing, and managing information related to reinforced concrete girder bridges. Therefore, when developing BIM solutions, interoperability issues, and application compatibility logics, in addition to application update times, should be taken into account [74,76,77]. In the development of the proposal covered by this paper, the authors considered the adoption of open formats (e.g., IFC) and APIs in addition to the use of a BIM collaborative platform, ensuring the compatibility of the developed solution among the several environments considered. In this way, data accessibility has been made independent of the specific solutions and times for all actors involved (bridge engineer, project manager, etc.). However, all these issues can be overcome and improved by other studies or developments that will also allow to consider this solution for other types of bridges (composite bridges, steel bridges, etc.). This will enable, by means of the development of additional methods and procedures, starting from the framework setting that has been arranged, for such future integrations by the authors. The further application of other open standards (e.g., bSDD, IDS, etc.) along with the openCDE APIs, will enable the guarantee of a better interoperability within the whole AECO software ecosystem for the infrastructure management such as existing bridges. Moving from the needs arisen in Sections 1 and 2, it can easily be understood how this proposal, supported by a specific IT framework along with information and data managed centered on BrIMs together managed in a unique collaborative environment, will favor expeditious evaluations (on risk, structural safety, condition status, etc.) of bridges, facilitating relative decision-making and management processes.

6. Conclusions

When managing large-scale infrastructure and related assets (e.g., bridges and viaducts), current regulations require innovative approaches that are drawn from different skills, and not only those related to structural engineering (e.g., computer science, electronics, etc.). The innovation of this proposal consists of the development and implementation of a digital solution for the storage, processing, and management of information based on tailor-made information models developed according to the appropriate information requirements arisen from context under investigation. As also shown in Section 2, there are no all-encompassing solutions for information management in the context analyzed (LGP, NTC and AINOP). Accordingly, the management of bridges, from census to the management of structural safety, has been included in an overall framework of information management that aims to ensure the appropriate safety level. This solution meets the regulatory requirements in terms of the progressive adoption of information models of the infrastructure, which allow the effective and transparent management of the asset through the use of common data environments and interoperable platforms of data, construction objects, and information models. In addition, this proposal could also lend itself to future integrations with other systems, such as BMS or ERP, for a closer integration with managing authorities' systems, enabling a higher-performing solution for bridge management activities. From census activities to the management of structural safety, the authors provide an effective solution for the management of bridges, ensuring an appropriate and reliable source of reference for acquiring information regarding the structure itself, as well as for tracing the evolution of risk and intervention priorities over time.

Author Contributions: Conceptualization, A.C., D.A., A.S. and M.N.; Data curation, A.C., P.S. and D.A.; Investigation, A.C. and P.S.; Methodology, A.C. and D.A.; Software, A.C. and P.S.; Supervision, D.A. and M.N.; Validation, A.C., P.S. and A.S.; Visualization, A.C. and P.S.; Writing—original draft, A.C., P.S. and D.A.; Writing—review & editing, A.C., D.A., A.S. and M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the companies "ANAS" and "Autostrade per l'Italia" for kindly providing the documentation related to the selected case studies.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kaewunruen, S.; Sresakoolchai, J.; Zhou, Z. Sustainability-based lifecycle management for bridge infrastructure using 6D BIM. *Sustainability* **2020**, *12*, 2436. [CrossRef]
2. Shim, C.S.; Dang, N.S.; Lon, S.; Jeon, C.H. Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. *Struct. Infrastruct. Eng.* **2019**, *15*, 1319–1332. [CrossRef]
3. Lu, Q.; Xie, X.; Heaton, J.; Parlikad, A.K.; Schooling, J. From BIM towards digital twin: Strategy and future development for smart asset management. *Stud. Comput. Intell.* **2020**, *853*, 392–404.
4. Dang, N.S.; Kang, H.; Lon, S.; Shim, C.S. 3D digital twin models for bridge maintenance. In Proceedings of the 10th International Conference on Short and Medium Span Bridges, Quebec City, QC, Canada, 30 July–3 August 2018; pp. 1–9.
5. Errandonea, I.; Beltrán, S.; Arrizabalaga, S. Digital Twin for maintenance: A literature review. *Comput. Ind.* **2020**, *123*, 103316. [CrossRef]
6. Sepasgozar, S.M.E.; Hui, F.K.P.; Shirowzhan, S.; Foroozanfar, M.; Yang, L.; Aye, L. Lean practices using building information modeling (Bim) and digital twinning for sustainable construction. *Sustainability* **2021**, *13*, 161. [CrossRef]
7. Cavka, H.B.; Staub-French, S.; Poirier, E.A. Developing owner information requirements for BIM-enabled project delivery and asset management. *Autom. Constr.* **2017**, *83*, 169–183. [CrossRef]
8. Byun, N.; Han, W.S.; Kwon, Y.W.; Kang, Y.J. Development of bim-based bridge maintenance system considering maintenance data schema and information system. *Sustainability* **2021**, *13*, 4858. [CrossRef]
9. Wan, C.; Zhou, Z.; Li, S.; Ding, Y.; Xu, Z.; Yang, Z.; Xia, Y.; Yin, F. Development of a bridge management system based on the building information modeling technology. *Sustainability* **2019**, *11*, 4583. [CrossRef]
10. Ciccone, A.; Di Stasio, S.; Asprone, D.; Salzano, A.; Nicolella, M. Application of openBIM for the Management of Existing Railway Infrastructure: Case Study of the Cancello–Benevento Railway Line. *Sustainability* **2022**, *14*, 2283. [CrossRef]
11. Bazán, Á.M.; Alberti, M.G.; Álvarez, A.A.; Trigueros, J.A. New perspectives for bim usage in transportation infrastructure projects. *Appl. Sci.* **2020**, *10*, 72. [CrossRef]
12. Shim, C.S.; Kang, H.; Dang, N.S.; Lee, D. Development of BIM-based bridge maintenance system for cable-stayed bridges. *Smart Struct. Syst.* **2017**, *20*, 697–708. [CrossRef]
13. Akcamete, A.; Akinci, B.; Garrett, J.H. Potential utilization of building information models for planning maintenance activities. In Proceedings of the EG-ICE 2010—17th International Workshop on Intelligent Computing in Engineering, Nottingham, UK, 30 June–2 July 2010.
14. McGuire, B.; Atadero, R.; Clevenger, C.; Ozbek, M. Bridge Information Modeling for Inspection and Evaluation. *J. Bridg. Eng.* **2016**, *21*. [CrossRef]
15. *MIT Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti*; Ministero delle Infrastrutture e dei Trasporti. Consiglio Superiore dei Lavori Pubblici: Rome, Italy, 2020.
16. Santarsiero, G.; Masi, A.; Picciano, V.; Digrisolo, A. The Italian Guidelines on Risk Classification and Management of Bridges: Applications and Remarks on Large Scale Risk Assessments. *Infrastructures* **2021**, *6*, 111. [CrossRef]
17. *ISO/TC 59/SC 13 ISO 19650-1:2018*; Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 1: Concepts and Principles. ISO: Geneva, Switzerland, 2018.
18. UNI. EN UNI EN 17412-1:2021. Available online: http://store.uni.com/catalogo/uni-en-17412-1-2021?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com (accessed on 1 March 2022).

19. Musella, C.; Serra, M.; Salzano, A.; Menna, C.; Asprone, D. Open BIM Standards: A Review of the Processes for Managing Existing Structures in the Pre- and Post-Earthquake Phases. *CivilEng* **2020**, *1*, 291–309. [CrossRef]
20. Borrmann, A.; Muhic, S.; Hyvärinen, J.; Chipman, T.; Jaud, S.; Castaing, C.; Dumoulin, C.; Liebich, T.; Mol, L. The IFC-Bridge project—Extending the IFC standard to enable high-quality exchange of bridge information models. In Proceedings of the 2019 European Conference for Computing in Construction, Crete, Greece, 10–12 July 2019; University College Dublin: Dublin, Ireland, 2019; Volume 1, pp. 377–386.
21. Sánchez-Rodríguez, A.; Esser, S.; Abualdenien, J.; Borrmann, A.; Riveiro, B. From point cloud to IFC: A masonry arch bridge case study. In Proceedings of the EG-ICE 2020 International Workshop on Intelligent Computing in Engineering, Online, 1–3 July 2020; pp. 422–431.
22. Jiang, S.; Jiang, L.; Han, Y.; Wu, Z.; Wang, N. OpenBIM: An enabling solution for information interoperability. *Appl. Sci.* **2019**, *9*, 5358. [CrossRef]
23. Moretti, N.; Xie, X.; Merino, J.; Brazauskas, J.; Parlikad, A.K. An openbim approach to iot integration with incomplete as-built data. *Appl. Sci.* **2020**, *10*, 8287. [CrossRef]
24. Sacks, R.; Kedar, A.; Borrmann, A.; Ma, L.; Singer, D.; Kattel, U. SeeBridge information delivery manual (IDM) for next generation bridge inspection. In Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2016), Auburn, AL, USA, 18–21 July 2016; pp. 826–834. [CrossRef]
25. Isailović, D.; Petronijević, M.; Hajdin, R. The future of BIM and Bridge Management Systems. In Proceedings of the IABSE Symposium. 2019. (3 Parts) Towards a Resilient Built Environment—Risk and Asset Management, Guimaraes, Portugal, 27–29 March 2019; pp. 1673–1680. [CrossRef]
26. Jensen, J.S. Innovative and sustainable operation and maintenance of bridges. *Struct. Infrastruct. Eng.* **2020**, *16*, 72–83. [CrossRef]
27. Artus, M.; Koch, C. Modeling geometry and semantics of physical damages using IFC. In Proceedings of the EG-ICE 2020 International Workshop on Intelligent Computing in Engineering, Online, 1–3 July 2020; pp. 144–153.
28. Esser, S.; Aicher, K. IfcBridge Model Generation using Visual Programming. In Proceedings of the Forum Bauinformatik 2019, Berlin, Germany, 11–13 September 2019; pp. 101–108.
29. Ding, L.; Li, K.; Zhou, Y.; Love, P.E.D. An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control. *Autom. Constr.* **2017**, *84*, 96–110. [CrossRef]
30. Tanaka, F.; Hori, M.; Onosato, M.; Date, H.; Kanai, S. Bridge Information Model Based on IFC Standards and Web Content Providing System for Supporting an Inspection Process. In Proceedings of the 16th International Conference on Computing in Civil and Building Engineering (ICCCBE 2016), Osaka, Japan, 6–8 July 2015.
31. Dang, N.S.; Shim, C.S. Bridge assessment for PSC girder bridge using digital twins model. *Lect. Notes Civ. Eng.* **2020**, *54*, 1241–1246. [CrossRef]
32. Cheng, J.C.P.; Lu, Q.; Deng, Y. Analytical review and evaluation of civil information modeling. *Autom. Constr.* **2016**, *67*, 31–47. [CrossRef]
33. Ait-Lamallam, S.; Sebari, I.; Yaagoubi, R.; Doukari, O. IFCInfra4OM: An ontology to integrate operation and maintenance information in highway information modelling. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 305. [CrossRef]
34. Abualdenien, J.; Borrmann, A. Levels of detail, development, definition, and information need: A critical literature review. *J. Inf. Technol. Constr.* **2022**, *27*, 363–392. [CrossRef]
35. Collao, J.; Lozano-galant, F.; Lozano-galant, J.A. BIM Visual Programming Tools Applications in Infrastructure Projects: A State-of-the-Art Review. *Appl. Sci.* **2021**, *11*, 8343. [CrossRef]
36. Girardet, A.; Boton, C. Automation in Construction A parametric BIM approach to foster bridge project design and analysis. *Autom. Constr.* **2021**, *126*, 103679. [CrossRef]
37. Blanco Rávena, R.; Martínez García, J.; Mozas González, B.; García Alberti, M.; Arcos Álvarez, A.A. Uso de la metodología BIM en la remodelación de un puente existente = Use of BIM methodology in the re-modelling of an existing bridge. *An. Edif.* **2019**, *5*, 100. [CrossRef]
38. Biancardo, S.A.; Viscione, N.; Cerbone, A.; Dessì, E. BIM-Based Design for Road Infrastructure: A Critical Focus on Modeling Guardrails and Retaining Walls. *Infrastructures* **2020**, *5*, 59. [CrossRef]
39. Hui, W.; Xu, H.; Li, Z.; Ma, C. Parametric Design and Application of Assembled Steel Plate Composite Beam Bridge Based on BIM Technology. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *371*, 022074. [CrossRef]
40. Biancardo, S.A.; Intignano, M.; Viscione, N.; Guerra De Oliveira, S.; Tibaut, A. Procedural Modeling-Based BIM Approach for Railway Design. *J. Adv. Transp.* **2021**, *2021*, 8839362. [CrossRef]
41. Biancardo, S.A.; Capano, A.; de Oliveira, S.G.; Tibaut, A. Integration of BIM and procedural modeling tools for road design. *Infrastructures* **2020**, *5*, 37. [CrossRef]
42. Biancardo, S.A.; Intignano, M.; Abramović, B.; Abbondati, F.; Dell'Acqua, G. Horizontal Building Information Modeling: The Croatian railway Gradec-Sveti Ivan Žabno case study. *Ing. Ferrov.* **2021**, *76*, 979–994.
43. Abbondati, F.; Biancardo, S.A.; Sicignano, G.; de Oliveira, S.; Tibaut, A.; Dell'Acqua, G. Bim parametric modelling of a railway underpass. *Ing. Ferrov.* **2020**, *75*, 443–459.
44. Pasetto, M.; Giordano, A.; Borin, P.; Giacomello, G. Integrated railway design using Infrastructure-Building Information Modeling. the case study of the port of Venice. *Transp. Res. Procedia* **2020**, *45*, 850–857. [CrossRef]

45. Zou, Y.; Kiviniemi, A.; Jones, S.W. A review of risk management through BIM and BIM-related technologies. *Saf. Sci.* **2017**, *97*, 88–98. [CrossRef]
46. Salamak, M.; Januszka, M. Brim bridge inspections in the context of industry 4.0 trends. In *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges. Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018), Melbourne, Australia, 9–13 July 2018*; CRC Press: London, UK, 2018; pp. 2260–2267. [CrossRef]
47. Zou, Y.; Kiviniemi, A.; Jones, S.W.; Walsh, J. Risk Information Management for Bridges by Integrating Risk Breakdown Structure into 3D/4D BIM. *KSCE J. Civ. Eng.* **2019**, *23*, 467–480. [CrossRef]
48. Vitiello, U.; Ciotta, V.; Salzano, A.; Asprone, D.; Manfredi, G.; Cosenza, E. BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings. *Autom. Constr.* **2019**, *98*, 90–101. [CrossRef]
49. Panah, R.S.; Kioumarsi, M. Application of building information modelling (BIM) in the health monitoring and maintenance process: A systematic review. *Sensors* **2021**, *21*, 837. [CrossRef] [PubMed]
50. Dang, N.S.; Shim, C.S. BIM authoring for an image-based bridge maintenance system of existing cable-supported bridges. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *143*, 012032. [CrossRef]
51. Artus, M.; Koch, C. State of the art in damage information modeling for RC bridges—A literature review. *Adv. Eng. Inform.* **2020**, *46*, 101171. [CrossRef]
52. Borin, P.; Cavazzini, F. Condition assessment of RC bridges. integrating machine learning, photogrammetry and bim. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2019**, *42*, 201–208. [CrossRef]
53. Zhao, Z.; Gao, Y.; Hu, X.; Zhou, Y.; Zhao, L.; Qin, G.; Guo, J.; Liu, Y.; Yu, C.; Han, D. Integrating BIM and IoT for smart bridge management. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *371*, 022034. [CrossRef]
54. Banfi, F.; Barazzetti, L.; Previtali, M.; Roncoroni, F. Historic bim: A new repository for structural health monitoring. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2017**, *42*, 269–274. [CrossRef]
55. Rio, J.; Ferreira, B.; Poças-Martins, J. Expansion of IFC model with structural sensors. *Inf. Constr.* **2013**, *65*, 219–228. [CrossRef]
56. Davila, M.; Butler, L.J.; Manuel Davila Delgado, J.; Brilakis, I.; Reader, R.; ZEB Elshafie, M.; Senior Lecturer, R.; Middleton, C.R.; Professor, R. Structural Performance Monitoring Using a Dynamic Data-Driven BIM Environment. *J. Comput. Civ. Eng.* **2018**, *32*. [CrossRef]
57. Theiler, M.; Smarsly, K. IFC Monitor—An IFC schema extension for modeling structural health monitoring systems. *Adv. Eng. Inform.* **2018**, *37*, 54–65. [CrossRef]
58. Floros, G.S.; Ellul, C. LOSS of INFORMATION during DESIGN & CONSTRUCTION for HIGHWAYS ASSET MANAGEMENT: A GEOBIM PERSPECTIVE. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *8*, 83–90. [CrossRef]
59. Pan, Y.; Dong, Y.; Wang, D.; Chen, A.; Ye, Z. Three-dimensional reconstruction of structural surface model of heritage bridges using UAV-based photogrammetric point clouds. *Remote Sens.* **2019**, *11*, 1204. [CrossRef]
60. Chan, B.; Guan, H.; Hou, L.; Jo, J.; Blumenstein, M.; Wang, J. Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. *J. Civ. Struct. Health Monit.* **2016**, *6*, 703–714. [CrossRef]
61. Lu, R.; Brilakis, I. Generating bridge geometric digital twins from point clouds. In Proceedings of the 2019 European Conference on Computing in Construction, Crete, Greece, 10–12 July 2019; Volume 1, pp. 367–376. [CrossRef]
62. Lu, R.; Brilakis, I. Digital twinning of existing reinforced concrete bridges from labelled point clusters. *Autom. Constr.* **2019**, *105*, 102837. [CrossRef]
63. Lu, R.; Brilakis, I.; Middleton, C.R. Detection of Structural Components in Point Clouds of Existing RC Bridges. *Comput. Civ. Infrastruct. Eng.* **2019**, *34*, 191–212. [CrossRef]
64. Popescu, C.; Täljsten, B.; Blanksvärd, T.; Elfgren, L. 3D reconstruction of existing concrete bridges using optical methods. *Struct. Infrastruct. Eng.* **2019**, *15*, 912–924. [CrossRef]
65. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [CrossRef]
66. Nordestgaard, P.M.; Jensen, J.; Mortensen, P.; Wyrtz, M.; Mikulenas, M.; Trifan, A.E. Application of Parametric Design in Project Containing Steel Structures: Parametric Light-Rail Steel Bridge. *Ce/Papers* **2019**, *3*, 767–772. [CrossRef]
67. Park, S.I.; Lee, S.H.; Almasi, A.; Song, J.H. Extended IFC-based strong form meshfree collocation analysis of a bridge structure. *Autom. Constr.* **2020**, *119*, 103364. [CrossRef]
68. Heaton, J.; Parlikad, A.K.; Schooling, J. Design and development of BIM models to support operations and maintenance. *Comput. Ind.* **2019**, *111*, 172–186. [CrossRef]
69. Dang, N.S.; Rho, G.T.; Shim, C.S. A master digital model for suspension bridges. *Appl. Sci.* **2020**, *10*, 7666. [CrossRef]
70. Chang, K.M.; Dzeng, R.J.; Wu, Y.J. An automated IoT visualization BIM platform for decision support in facilities management. *Appl. Sci.* **2018**, *8*, 1086. [CrossRef]
71. Bucher, D.F.; Hall, D.M. Common data environment within the AEC ecosystem: Moving collaborative platforms beyond the open versus closed dichotomy. In Proceedings of the EG-ICE 2020 International Workshop on Intelligent Computing in Engineering, Online, 1–3 July 2020; pp. 491–500.
72. Poinet, P.; Stefanescu, D.; Papadonikolaki, E. Collaborative Workflows and Version Control Through Open-Source and Distributed Common Data Environment. *Lect. Notes Civ. Eng.* **2021**, *98*, 228–247. [CrossRef]

73. Davila Delgado, J.M.; Oyedele, L.O. BIM data model requirements for asset monitoring and the circular economy. *J. Eng. Des. Technol.* **2020**, *18*, 1269–1285. [CrossRef]
74. Grilo, A.; Jardim-Goncalves, R. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* **2010**, *19*, 522–530. [CrossRef]
75. Eastman, C.M.; Jeong, Y.-S.; Sacks, R.; Kaner, I. Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards. *J. Comput. Civ. Eng.* **2010**, *24*. [CrossRef]
76. Zhang, P.; Portillo, L.; Kezunovic, M. Compatibility and interoperability evaluation for all-digital protection system through automatic application test. In Proceedings of the 2006 IEEE Power Engineering Society General Meeting, Montreal, QC, Canada, 18–22 June 2006; pp. 1–7. [CrossRef]
77. Shirowzhan, S.; Sepasgozar, S.M.E.; Edwards, D.J.; Li, H.; Wang, C. BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Autom. Constr.* **2020**, *112*, 103086. [CrossRef]
78. Ait-Lamallam, S.; Yaagoubi, R.; Sebari, I.; Doukari, O. Extending the IFC Standard to Enable Road Operation and Maintenance Management through OpenBIM. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 496. [CrossRef]
79. Lutz, M. *Learning Python*; O'Reilly: Sebastopol, CA, USA, 2008; ISBN 9780874216561.
80. Xu, X.; Huang, Q.; Ren, Y.; Zhao, D.Y.; Zhang, D.Y.; Sun, H. Bin Condition evaluation of suspension bridges for maintenance, repair and rehabilitation: A comprehensive framework. *Struct. Infrastruct. Eng.* **2019**, *15*, 555–567. [CrossRef]
81. Huston, D.; Burns, D.; Razinger, J. Structural health monitoring and maintenance aided by building information modelling and repair information tools. *Sustain. City XI* **2016**, *1*, 897–907. [CrossRef]
82. León-Robles, C.A.; Reinoso-Gordo, J.F.; González-Quiñones, J.J. Heritage building information modeling (H-BIM) applied to a stone bridge. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 121. [CrossRef]
83. Sacks, R.; Kedar, A.; Borrmann, A.; Ma, L.; Brilakis, I.; Hüthwohl, P.; Daum, S.; Kattel, U.; Yosef, R.; Liebich, T.; et al. SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition. *Autom. Constr.* **2018**, *90*, 134–145. [CrossRef]