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Customized Approaches for Introducing Road Maintenance Management in I-BIM Environments

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Abstract: Road maintenance management aims to satisfy quality, comfort, and safety requirements for the various assets. To overcome delays and barriers in the widespread adoption of road management systems, the Building Information Modeling (BIM) approach may offer significant advantages as a convenient alternative for road maintenance management. Although existing BIM platforms are not fully equipped for this purpose, defining original modules and scripts can extend their capabilities, allowing for the handling of road condition information and maintenance management. In this context, this paper presents an operative framework designed to leverage BIM benefits for road maintenance management, particularly in terms of virtual inspection, asset condition assessment, and maintenance design. To achieve this, specific original and customized smart objects and routines were coded in I-BIM platforms, tailored to different scales, aims, and detail levels. These smart objects incorporate user-defined extended attributes related to pavement condition and maintenance planning (such as roughness, rutting, structural capacity). In particular, the authors have developed original virtual smart objects in different platforms, serving as "containers" for the survey information. These objects are adapted to display quality levels of the pavement segments in a realistic and user-friendly environment. Additionally, original routines were coded to automatically import survey data from external datasets and associate this information with the appropriate objects. This customized and extended approach, not available in commercial platforms, can effectively support maintenance operators.

Keywords: pavement condition; road asset management; building information modeling; pavement maintenance; pavement attributes

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1. Introduction

To guarantee optimal conditions for economic development while ensuring safety and comfort for vehicular traffic, all components of road transport infrastructures must remain efficient throughout their useful life. To this end, with a view to an "integrated project", correct design and construction are necessary. Furthermore, during the phases of use and operation, an appropriate and conscious approach to the complex problems related to maintenance is required to ensure the reliability of all components over time in terms of performance and safety [1]. Despite significant expenses in maintenance and rehabilitation activities, various conditions—such as increasing traffic loads, deteriorating of pavement conditions, and lack of adequate condition knowledge—make these goals challenging [2]. In general, knowing the "health" state of all infrastructure components can guarantee the formulation of reliable plans and strategies in the short, medium, and long term, at different project scales [3]. An adequate and up-to-date knowledge of the asset condition is crucial for better predicting and planning maintenance activities at both the network and project levels, maximizing intervention effectiveness, and ensuring a correct and optimal allocation of available budgets.

Traditionally, the planning of road infrastructure maintenance has relied on road management systems (RMSs), i.e., computerized management systems consisting of several modules for various road assets. Pavement management systems (PMSs) are specific modules for road pavement management. They utilize decision support algorithms based on databases containing historical data, construction types, operation details, monitoring and control activities, and past maintenance interventions. However, effective productive management requires a complete and adequate knowledge of the pavement condition and of the degradation of its structural and functional characteristics [3]. Modern technologies based on digital systems and models have recently opened new opportunities for monitoring activities using innovative techniques capable of detecting large amounts of information (big data) in real time. Specifically, as highlighted in various studies and applications [4–6], the most modern high-performance surveying systems (including 3D surveying techniques) can acquire huge amounts of data with high density. However, adequate methodologies for exploiting the potential of such data in user-friendly software and platforms have not been defined yet [7].

Traditional PMSs, despite their methodological rigor, lack simplified interfaces, immediately usable and easy to manage for operators. This has historically complicated their practical application, leading to inconsistent usage [8,9]. Therefore, it is necessary to implement new procedures for managing collected data to achieve two main objectives: (1) simplify the methods of managing, processing, and displaying survey results, and (2) identify a modern decision support model for maintenance purposes that is derived from traditional PMSs but optimized and with an easy-to-use interface. Modern Building Information Modeling (BIM), which has been a convenient and reliable solution in various areas of civil engineering for several decades [10], appears potentially suitable for this problem.

Despite the evident potential advantages, the adoption of BIM solutions in the infrastructure field (I-BIM: infrastructure building information modeling) has primarily focused on design and execution phases rather than maintenance management [11–14]. Aspects related to operation and maintenance phases for road infrastructures are not effectively exploited, despite potential benefits in representation clarity, realistic modeling, immediate querying, and virtual inspection [7]. A few previous studies have preliminarily discussed the potential benefits of this approach for maintenance and rehabilitation phases, aiming to evolve current PMS procedures and integrate them into more user-friendly and intuitive solutions in realistic and complete I-BIM environments [7,15,16]. Additionally, current international and national regulations (such as European Directive 2014/24/EU [17] and both DM 560/2017 [18] and DM 312/2021 [19] for Italy) are progressively mandating a transition towards digital models and solutions for infrastructure projects, which will also impact maintenance and rehabilitation phases.

In light of this framework, the objective of this research has been the definition of original protocols and operative methodologies within I-BIM environments commonly used in the professional field for analyzing, processing, and elaborating survey data related to asphalt pavements. The approach involved specific I-BIM environments, naturally oriented to the design phase, to create a comprehensive vision that, starting from field survey evidence, can be used to define and design maintenance and rehabilitation interventions in a unified, optimized, and realistic environment.

For this aim, the authors have investigated the representation, elaboration, and design opportunities of I-BIM environments, specifically enhanced by the definition of original and customized smart objects and processing routines. The aim of the paper is to define the I-BIM-based approach for information management and data analysis from a methodological point of view. For testing purposes, the proposed approach was applied in Autodesk® Infraworks® 2022 and Civil3D® 2022 software, taking full advantage of the realistic 3D modeling of infrastructures and the environment in the former and the modeling opportunities and intervention design features in the latter. The selected software environments serve only as operative examples of the proposed innovative approaches, which can be adapted to different I-BIM environments, such as those presented in [13].

In detail, the results of a detailed survey campaign performed on an existing motorway in southern Italy were automatically loaded into the I-BIM environment through specific original routines, for simplifying visualization and graphical evaluation of pavement conditions and creating a link with the subsequent intervention design phase. The proposed solutions demonstrate the potential of alternative approaches in I-BIM to handle maintenance aspects and issues. Existing commercial solutions cannot directly store and process condition and maintenance-related information and lack specific processing procedures and algorithms for maintenance management purposes. Consequently, this research provides an opportunity to improve current approaches by extending the potential of BIM methodologies to the infrastructure sector.

In the following sections, after a brief literature review on I-BIM solutions in the infrastructure sector, the reference database and the methodological framework are presented. The results on the selected case studies are then provided and discussed, evidencing the advancements and benefits of the proposed approach. This framework, by enriching I-BIM environments with novel solutions, can effectively support maintenance operators in their tasks.

2. Background

Maintaining roads in appropriate and adequate conditions for their entire life cycle is a relevant challenge for road administrators. To achieve this target, robust management and optimization solutions are required, especially when in case of limited budgets and resources. With the widening of the road network and the increase in traffic, when the first degradation issues appeared, specific computer-based support tools were developed for simplifying network management and maintenance strategy planning. Beyond database solutions, the introduction of the Geographic Information System (GIS) represented a positive innovation for PMSs and RMSs [2,20–22]. It, in fact, ensures clearer representation of road and pavement characteristics, at network scale, on maps, favoring more confident condition evaluation and maintenance decisions. However, traditional PMSs present considerable limitations in terms of use complications, representation limits, and lack of entire life cycle handling (especially in terms of design and rehabilitation phases) and of a complete infrastructure model [8,15].

To overcome some of these limitations, BIM has been studied as a potential alternative approach for improving maintenance management phases of infrastructure systems, exploiting the related management advantages [23]. Recent European and national policies aiming to fully digitalize the construction sector even for maintenance and management projects, for improving efficiency and productivity, increased the attention on this transition.

Infrastructure-related BIM solutions, uses, and case studies are continuously increasing [12,24]. Despite an initial gap with the building sector, increasing attention and relevant dedicated efforts have been pushing I-BIM to remarkable levels, especially for design and construction phases [14,25–30]. Considering in particular road maintenance and management phases, some methodological approaches, technical applications, and procedural frameworks have been slowly proposed, evidencing the clear benefits related to management improvement, asset condition knowledge exploitation, realistic modeling, user-friendly environment, and coding opportunities for introducing analytical tools derived from traditional PMSs [7,23,25,31]. After some initial methodological analyses and proofs of concept [7,31], specific applications were effectively proposed. For example, despite being developed in Revit®—not an infrastructure-oriented environment—a preliminary and simplified maintenance framework, based on Dynamo® algorithms, is proposed in [16]. Similarly, Cho et al. [32] defined an operative framework dedicated to spalling maintenance. Considering, instead, specific solutions for I-BIM environments, Bosurgi et al. [15] proposed an original pavement condition information modeling framework, paving the way for the exploitation of survey data and information related to maintenance management and planning. In this research, the authors specifically defined original smart objects, enriched with condition information derived from high-performance surveys, to handle pavement quality data on a realistic model of the road and of the environmental context. The original routines proposed by the authors allow the operators to automatically import road condition data in the related infrastructure components and to easily investigate the road conditions through different visualization and analysis tools, for more sound and robust decision making. Once specific and customized variables can be input and processed in the BIM environments, even sustainability-based or life cycle cost analysis (as in [33], even though in this case the analysis is performed on an entire corridor basis) can be implemented to support the decisional phases.

However, currently, these applications only represent partial and preliminary steps towards the more comprehensive perspective of introducing PMS-derived protocols and procedures in I-BIM environments. Consequently, upgrading existing solutions to properly handle maintenance management topics and for also defining a direct link with the rehabilitation activity design phases is still necessary. This can also ensure operation with a unified model and in a unique environment for overall infrastructure life cycle management (from planning and design to construction, use and management, and maintenance and rehabilitation phases), as expected in BIM philosophy [23].

3. Pavement Survey Database

The procedural frameworks proposed for handling maintenance management information in I-BIM environments relied on an available dataset of reliable road pavement condition data. According to literature and practice, quality indicators of pavement structural and functional capacities (in terms of friction, structural capacity, roughness, distress density, etc.) are extremely precious variables. Based on previous research applications [8,15], the authors adopted conditions and quality survey data generally available to road administrators as a preliminary dataset. Considering a detailed monitoring activity performed on a motorway in southern Italy, the following status indicators (SIs) were involved:

- SNeff [34], derived from falling weight deflectometer (FWD) test elaborations;
- roughness (in terms of international roughness index—IRI) and rutting (rut depth—RD), measured using laser profilers;
- surface distress (pavement condition index—PCI).

These indicators were also combined in a synthetic quality index, named Critical State Index (CSI), aiming to attribute a unique condition level to the different pavement segments [15]. In its formulation, this index represents an efficient approach at the network level for a macro-identification of the critical segments that first require detailed analyses aimed at design and execution of maintenance interventions. For this purpose, CSI can vary between 1 (CSI = 1 refers to a pavement segment in good condition) and 4 (CSI = 4 refers to a pavement in an overly critical state).

4. I-BIM Original Solutions and Elaboration Frameworks

According to the research scope and aims, the modeling activity was specifically performed using I-BIM platforms only, i.e., BIM platforms defined and optimized for infrastructures. In this study, for testing purposes, acquisition, elaboration, data presentation, and the subsequent preliminary definition of the rehabilitation interventions were performed using Autodesk® Infraworks® 2022 and Civil 3D® 2022 software. The methodological approaches described in the following paragraphs and synthetized in the flowchart provided in Figure 1 were defined on an experimental segment of the selected motorway, 1 km long. All the variables and algorithms considered in this first attempt represent only preliminary means for testing the proposed method which is actually fully customizable and adaptable to other analysis solutions.

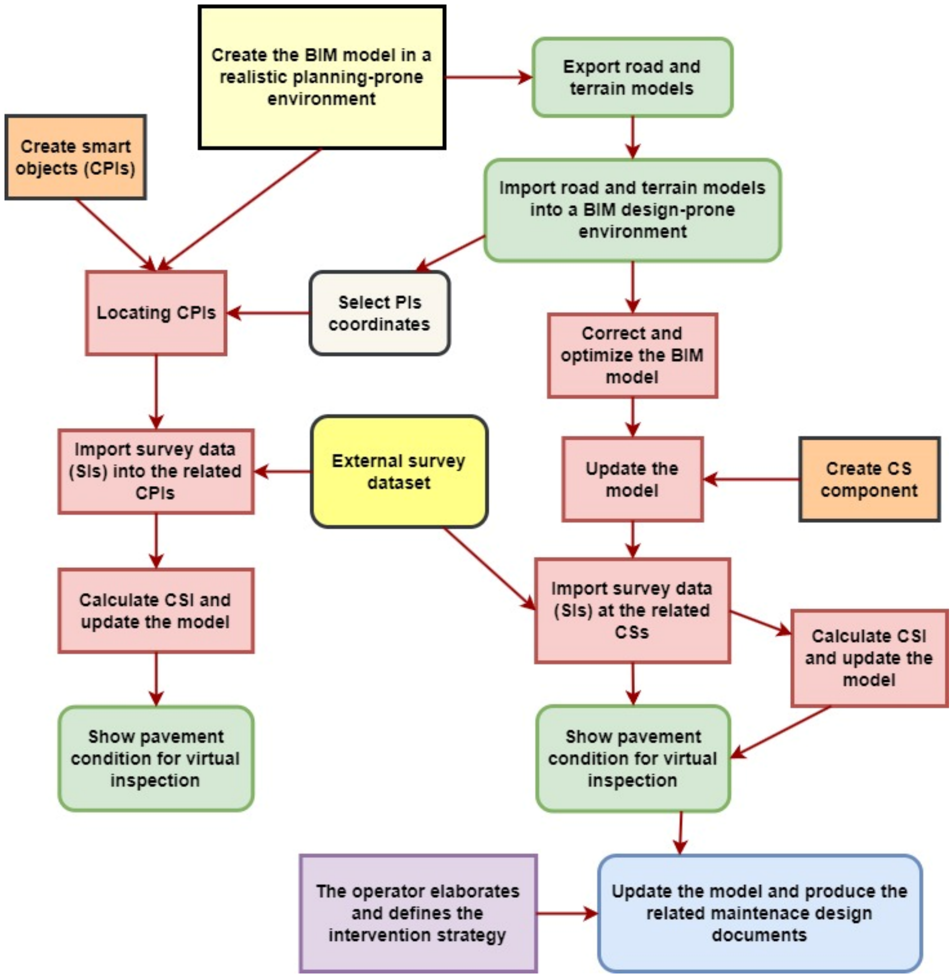


Figure 1. Flowchart of the proposed operative framework (CPI: Condition Point of Interest; PI: Point of Interest; CS: Condition Subassembly; SI: State Indicator; CSI: Critical State Index).

4.1. *Pavement Condition Information Modeling in a Realistic I-BIM Environment*

The proposed approach aims to address two of the most important BIM uses: "visualization" and "virtual inspection of constructions". Then, the first step is the construction of a complete infrastructure information model, including the territorial, geographical, and satellite information. Considering the testing environment (i.e., Autodesk® Infraworks®) this was preliminarily defined through the Model Builder cloud service that imports into the BIM database a series of data layers related to the specified area. This solution, despite being simplified and with a medium accuracy, allows the analyst to derive a first model of the infrastructure and of the external context, evidencing with acceptable approximation the entire existing road and rail network, as well as other contextual elements such as buildings, rivers, etc. All these elements are linked to a georeferenced digital elevation model (DEM) and covered with satellite images to create an extremely intelligible and clear immersive visualization (Figure 2). To obtain models with higher levels of detail and for rugged orographic areas, external data sources can be specifically used for importing plano-altimetric surveys of buildings, roads, and other georeferenced elements derived from more accurate GIS datasets or obtained through modern survey systems, such as mobile mapping systems or LIDAR [13,35,36]. According to the aims of the research, even a simplified, but realistic, representation of the asset and the environment is enough for investigating the methodological approaches and evaluating the potential benefits.

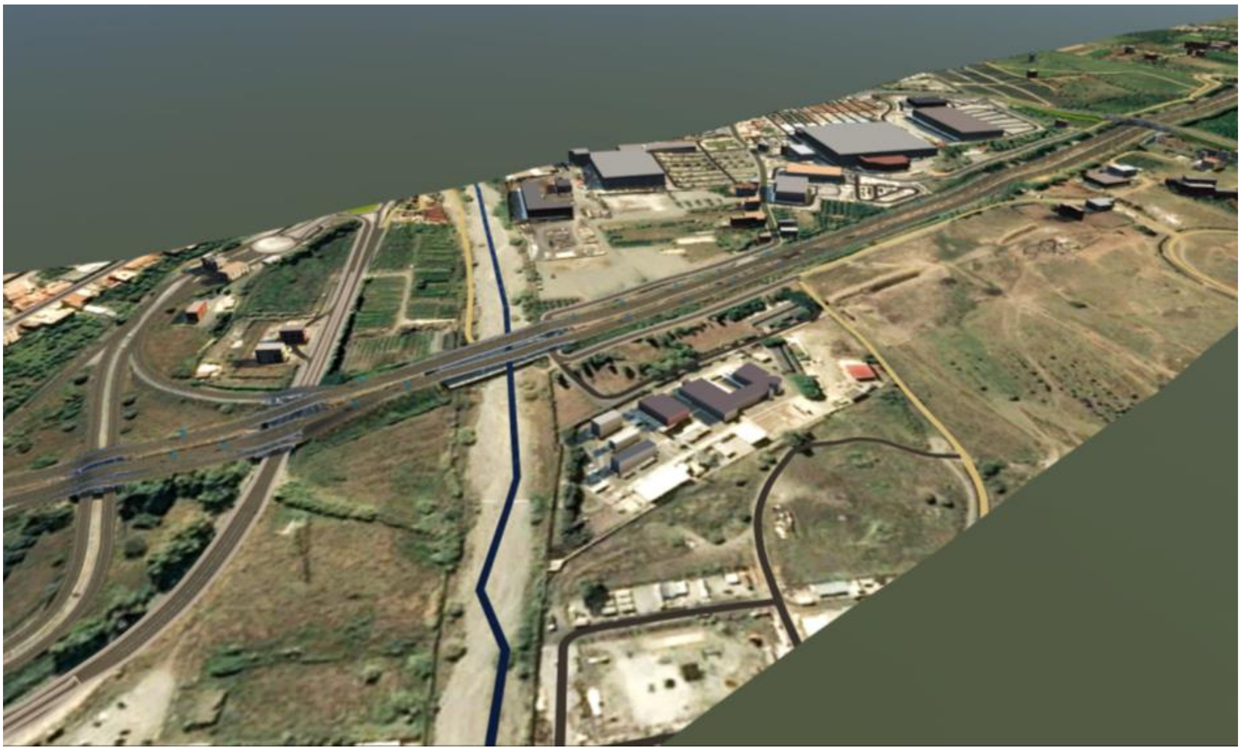


Figure 2. The 3D model of the selected motorway segment with satellite images in the I-BIM environment.

In this experimental test, the built-in smart objects representing the motorway segments were not changed. Instead, condition and survey information was added to novel specific virtual smart objects, helpful for representation improvements too. This choice determines an alternative "target container", in which introducing the customized information described in Section 3.

The idea was to use parametric "point of interest" (PI) objects and exploit their shape characteristics to also determine an alternative way to graph the survey results along the analyzed infrastructure, i.e., the values of the SIs. In detail, by using 3D parametric vector graphics software, symbolic cylindrical elements with parametric height and modifiable surface color were created (Figure 3). These, named in the following condition points of interest (CPIs), once imported into the I-BIM environment, serve as "containers" for the extended attributes related to the SIs at the various stations.

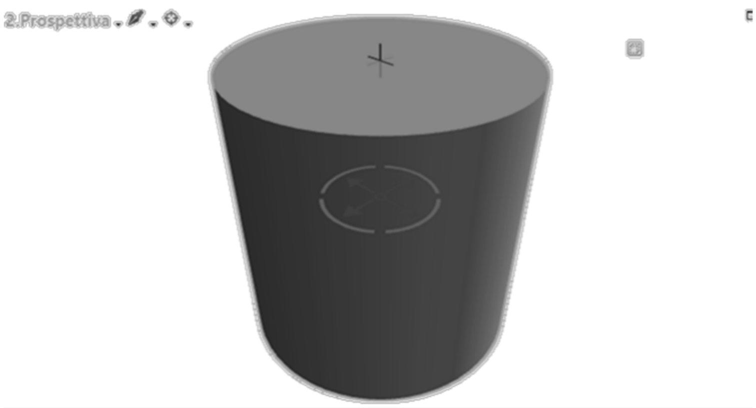


Figure 3. The 3D object (CPI) defined as a "container" of the extended attributes derived from surveys.

According to the dataset features presented in Section 2, condition information for each segment of the carriageway is available with different sampling frequencies for the various SIs. However, for improving representation clarity, a reference 1 m basis was fixed. Consequently, for each variable, the same value is repeated for different CPIs to cover the related sampling length (generally varying from 10 to 100 m). Then, the various target coordinates for the CPIs at the various stations were identified.

In detail, two groups of CPIs were defined: the first one includes four parallel CPIs for each station (one for each SI: SNeff, IRI, PCI, RD), the second one only the synthetic CSI value. In Figure 4, an example view of a road segment with the multiple original CPIs created for the 4 specific SIs is provided. In this status, the CPIs are "empty" since no extended attributes were imported in the model database yet.

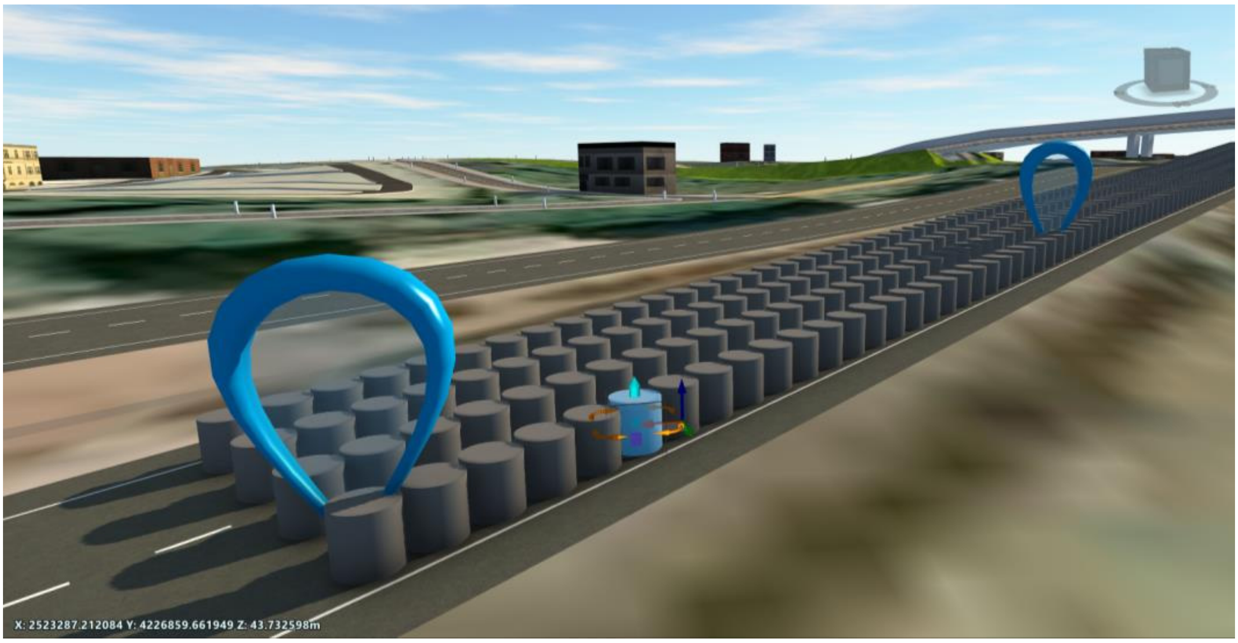


Figure 4. View of the "empty" CPI smart objects for the various SIs along a selected road segment.

All the CPIs are characterized by two different parameters calculated proportionally to the SI value at that station: a "double" class parameter to control its height and an "integer" class for its surface color. In detail, the second attribute refers to specific threshold values related to the acceptance or alert limits of the various SIs [8,15].

Then, through an original JavaScript routine directly operating on the internal structure of the model relational database, the authors defined an automated procedure to quickly assign the appropriate survey data to each CPI. This script for automated data import and processing made it possible to:

- assign to each station the corresponding value of the available SIs (SNeff, RD, IRI, and PCI), with a criterion of proximity to the sampling stations during surveys;
- assign to each parametric smart object and at each station a height proportional to the SI value to allow a sort of visual comparison of the critical conditions of the various sections by an immediate evaluation of a 3D bar diagram drawn along the road;
- assign a condition class (from 1 to 4) to each indicator at each station according to the reference thresholds and, at the same time, assign to each class a specific color (from good to bad conditions: Class 1, dark green; Class 2, light green; Class 3, yellow; Class 4, red) that allows another immediate assessment of the most critical sections;
- calculate the synthetic pavement quality value, in terms of CSI, at each station to provide a clear and immediate representation of the overall pavement conditions in a dynamic and 3D form.

4.2. Pavement Condition Analysis and Rehabilitation Intervention Definition in a Design-Oriented I-BIM Environment

The same selected motorway segment was also processed in Civil3D® to extend the BIM uses of the I-BIM-based maintenance management vision to the intervention design. Taking advantage of the software interoperability, the three-dimensional alignment (Figure 5) and the cross-section of the road defined in Section 4.1 were exchanged between the two environments.

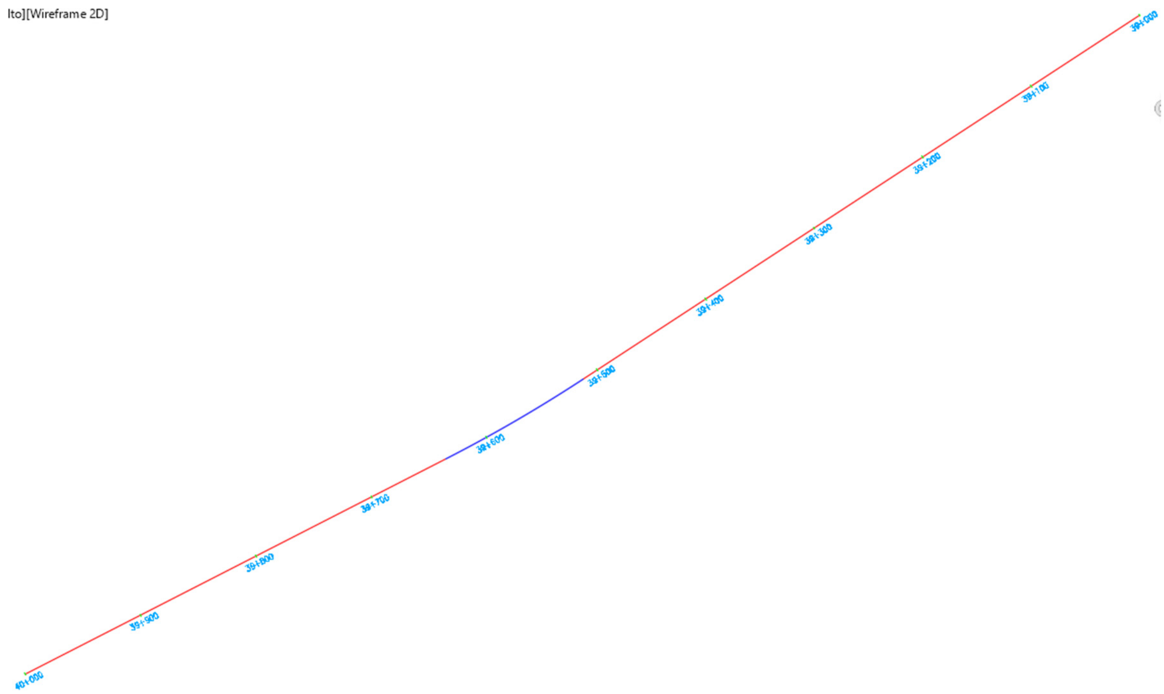


Figure 5. Alignment view of the selected motorway segment.

This activity, obviously, must be performed in a more accurate and detailed environment to ensure adequate project representation quality. Defining the complete 3D model of the road with a suitable level of definition (LOD from D to G) requires upgrading the cross-section, defined in terms of a subassembly group in the operative framework. The standard cross-section was conventionally defined by assuming symmetrical lanes, shoulders, and slopes and typical asphalt pavement consisting of 4 layers (subbase, base, binder, and surface courses), adapted to the specific example (Figure 6). Naturally, the pavement model can be fully customized according to the existing conditions.

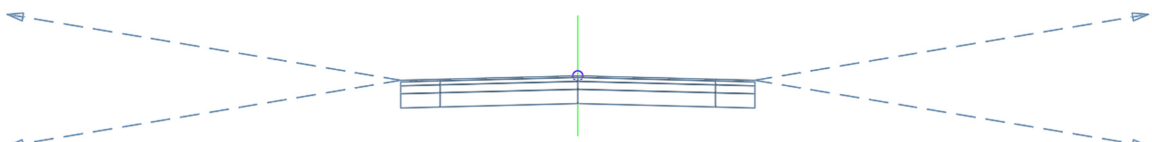


Figure 6. Selected assembly in the I-BIM environment to represent the cross-section of the road.

Considering the design operative workflow, once both the 3D alignment and the cross-sections are defined, a 3D solid model of the entire road can be defined (Figure 7). In compliance with the research aims, this model can be used to produce the technical documents describing, at the design stage, the selected maintenance interventions. However, this selection must rely on an adequate knowledge of the pavement conditions and having this information available in the same operative environment, during the decisional phases, can be crucial. This task required the conceptualization of novel and original solutions, since there are no available built-in functions in commercial BIM platforms.

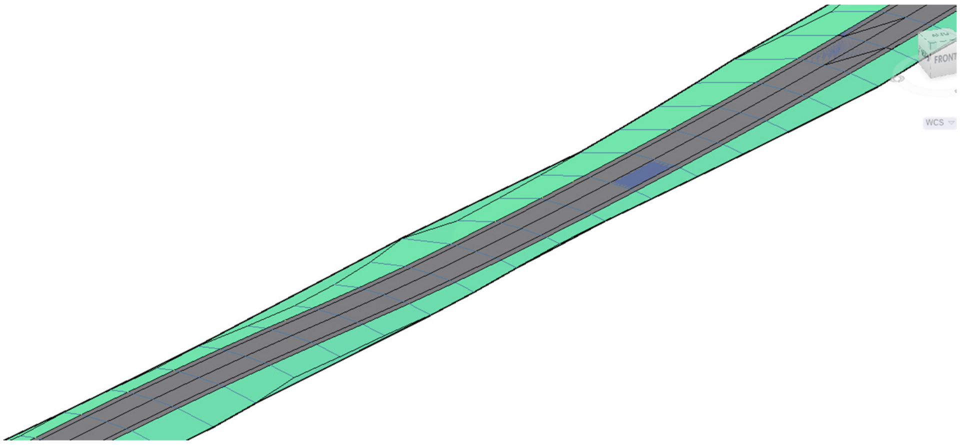


Figure 7. Example view of the corridor representing the 3D model of the road at the design stage, also evidencing the pavement structure, the section components, and the terrain grades.

Then, the authors tested the possibility of showing pavement conditions in the cross-section views, ensuring an immediate visual link with the different segments of the infrastructure, for supporting the subsequent decisional stages. This procedure required specific customization of the elaboration framework; in particular, a customized virtual component of the cross-section was originally defined. As in Section 4.1, this element acts as an "information container", for visualization purposes and is effectively linked to the same alignment of the corridor. This element is called in the following "condition subassembly" (CS), as it becomes part of the assembly defining the road corridor cross-section. The CS involves "not real" customized smart objects, used only for storing and representing the condition data derived from surveys (such as the CPIs in Section 4.1). Specific extended attributes, customized in compliance with the survey data features and the aim of the research, were defined for the CS. The CS object was designed and created in a dedicated environment by defining various display bars representing the quality classes for the various SIs. An example view of the CS definition approach is provided in Figure 8. CS was conceived as a combination of geometrical parametric objects (points, links, and shapes) that can be linked to the SI values through customized input and output parameters and original processing routines.

On this basis, specific CSs were conceived and defined for all the SIs listed in Section 3, i.e., SNeff, RD, IRI, and PCI. The reference values, for graphical benefits, were normalized to make the CSs mutually comparable. The various CSs, then, were assembled in the I-BIM environment as part of a novel virtual assembly (Figure 9a) which was connected to the road geometry, defining a virtual corridor representing the condition information variation along the road segments. Analogously, a similar procedure was also applied to a further CS referring to the CSI (Figure 9b).

At this stage, in truth, the various CSs have empty extended attributes, since there is not a built-in function to link the survey results and the reference visualization components. Then, this task requires further specific customized solutions that can rely on specific routines developed in Dynamo®—a powerful tool conceived for parametric visual coding, aiming at automatizing some activities in the BIM environment—the feasibility and convenience of which was investigated in this research. In the proposed framework, this tool was used to define original routines to (1) read and import the single values of the SIs stored in external digital datasets, (2) assign each of these values to the specific CSs, according to their geographical information, (3) calculate the CSI values for each section referring to each segment as a function of the values of the reference SIs and characterize the related CSs. The overall original routines proposed for these tasks are schematically represented in Figure 10.

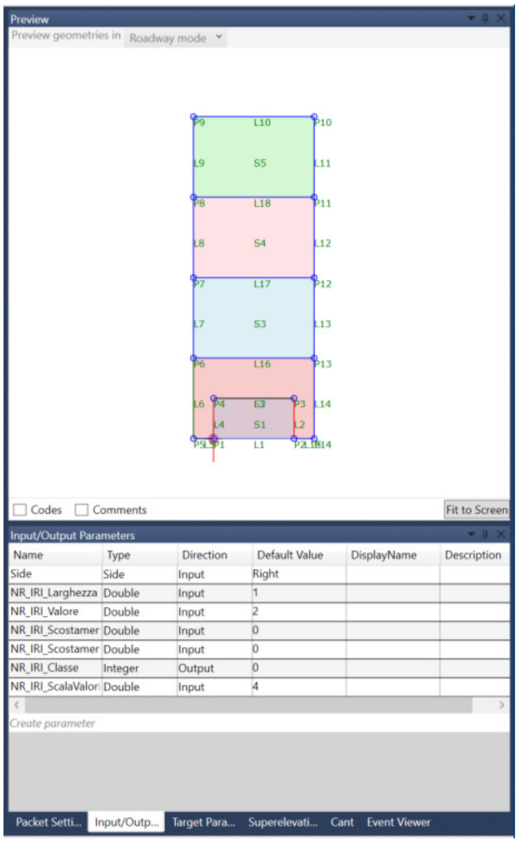
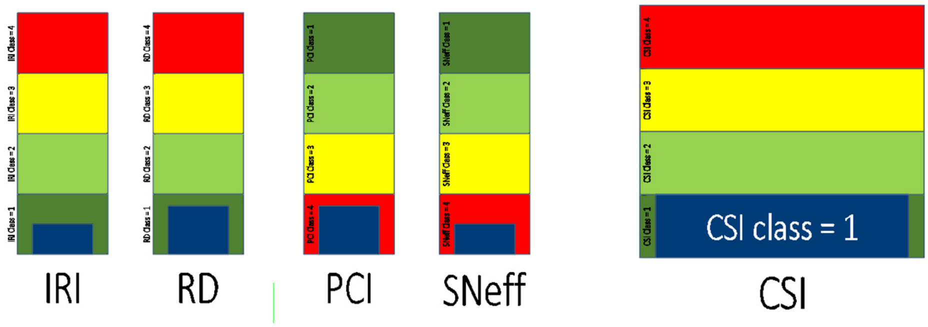


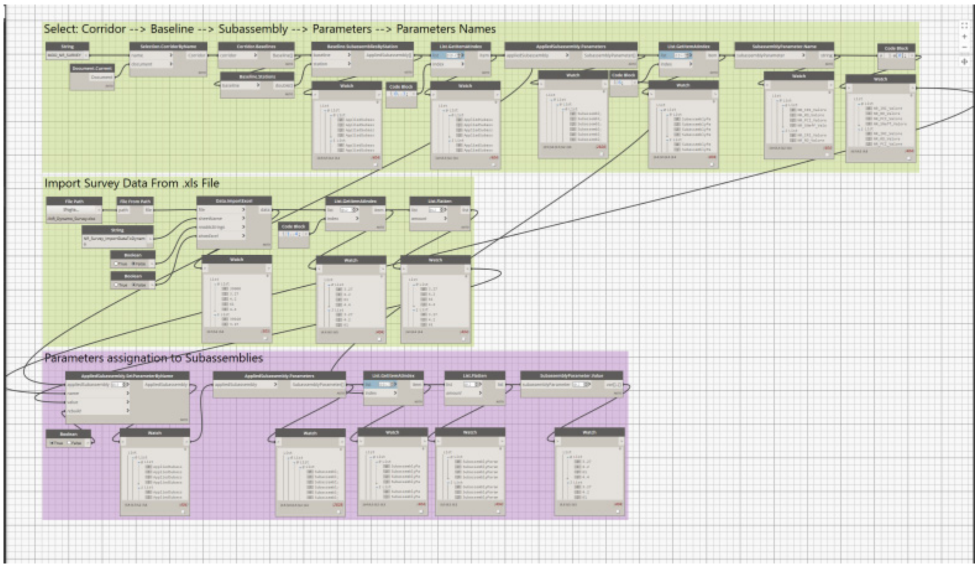
Figure 8. Example representation of CS conceptualization and design for one of the SIs.

As a result, the road segment condition can be graphically perceived even in a design-based environment, since the bars representing SIs and CSI are proportionally sized, with clear evidence of the related quality level. As anticipated, however, the procedure presented in this section aims to exploit other BIM uses than those related to visualization and virtual inspection of the infrastructure. Then, another visual script was developed for performing a preliminary maintenance design of the pavement, in which, in a preliminary example, interventions can be selected according to SIs and CSI values at each reference segment. For testing the methodological framework, in this context, a conventional intervention catalogue, characterized by different restoration depths for specific classes of degradation and critical conditions, was defined. A conceptual scheme of the related visual code is provided in Figure 11. In this work, the decision-making criterion and the possible intervention types were deliberately simplified since the purpose of the work is to demonstrate the suitability of the procedural framework. The proposed approach relies on original scripts and routines in BIM environments that are typically oriented towards other purposes to develop effective processes for managing road maintenance. Future developments of this research can involve more detailed analysis methods and intervention catalogues, incorporating more rigorous and advanced algorithms even derived from PMSs.

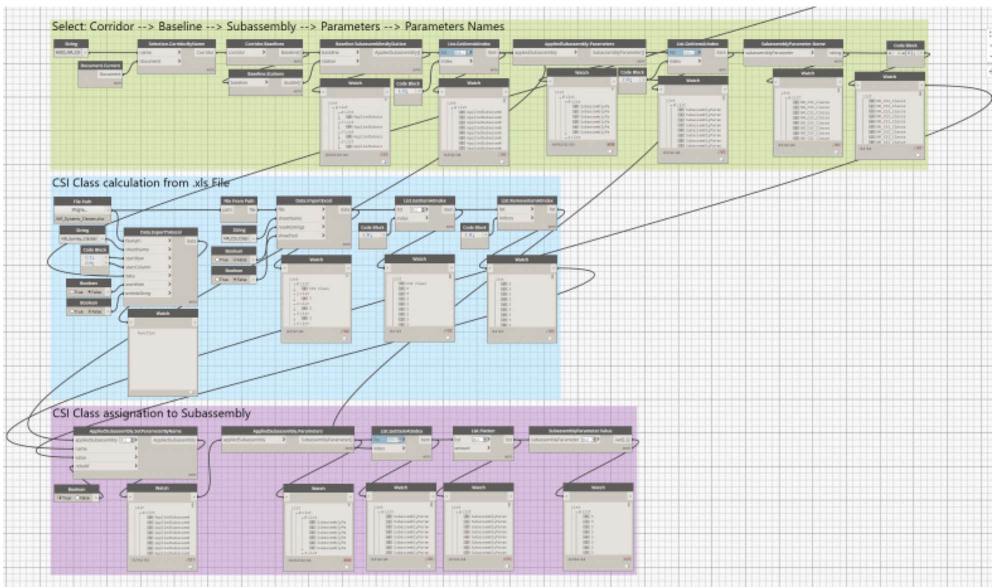


(**a**) (**b**)

Figure 9. CS examples for the basic SIs (**a**) and for the synthetic CSI (**b**).



(**a**)



(**b**)

Figure 10. Conceptual diagrams of originalobject-based code for assigning survey information to the various CSs (**a**) and to calculate and represent CSI values (**b**).

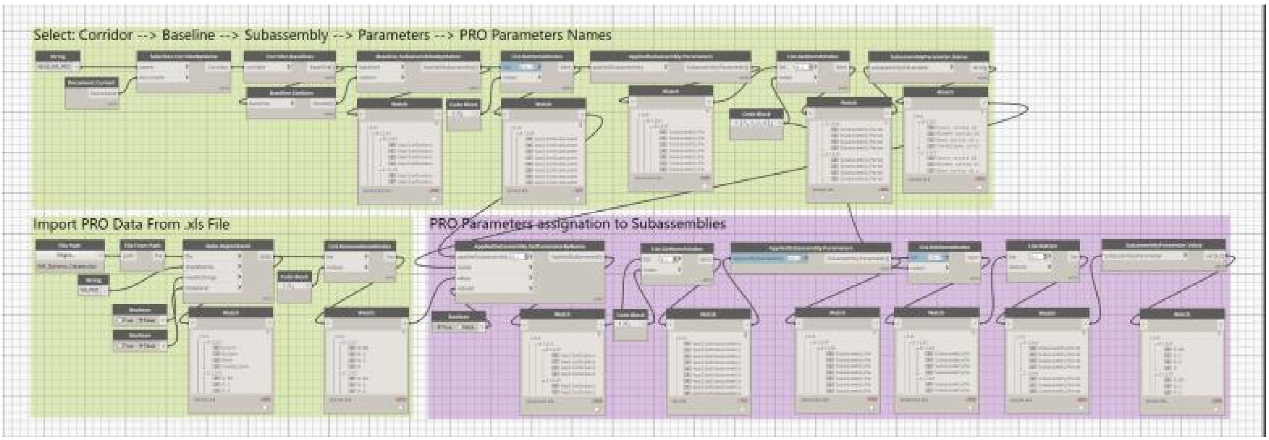


Figure 11. Conceptual diagram of original object-based code for intervention proposal based on the values of SIs and CSI at each section.

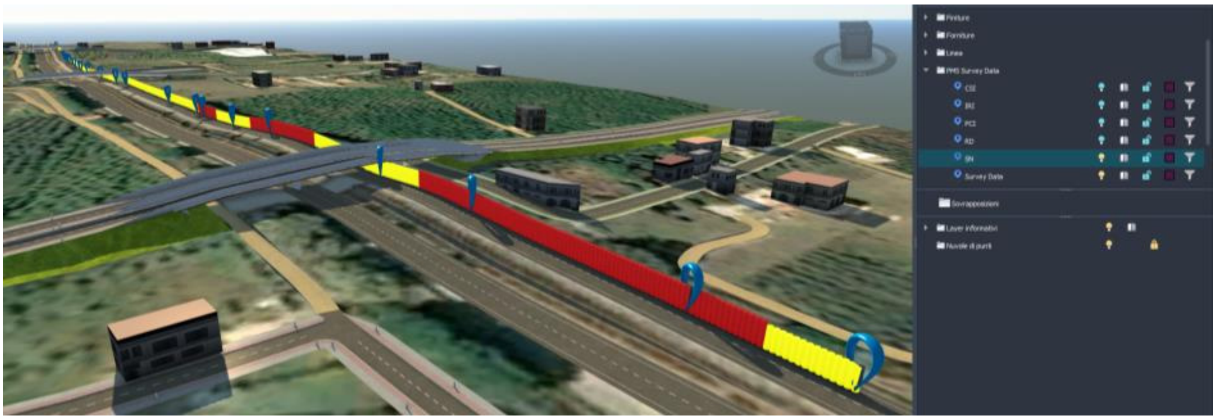
5. Case Study Applications

As anticipated, the methodological experiment regarded a case study focused on a portion of the Italian A20 motorway. In this section, the results of the two frameworks on the selected road segments are presented.

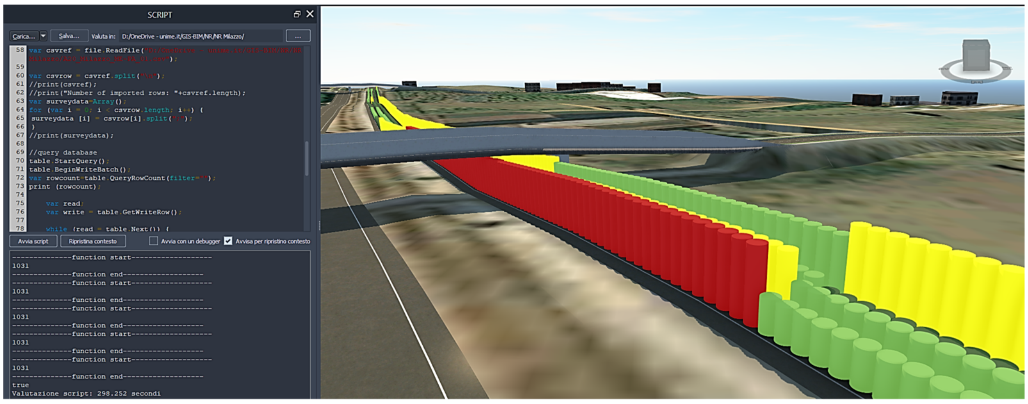
Considering the approach discussed in Section 4.1, once the various test stations were located in the global model and the various CPIs were introduced in the 3D model, the characterization routines were executed to load the different SI attributes extracted from the external database. Additionally, the CSI calculation routine is performed to evaluate this synthetic indicator and characterize the related "container".

Once the model is updated, it can be directly analyzed in the realistic I-BIM environment, exploiting benefits of visualization and virtual inspection. Indeed, the CPIs act as continuous 3D bar diagrams along the selected infrastructure, ensuring an immediate understanding of pavement conditions at the various segments. This can be performed in terms of the single SI (Figure 12a), of the various SIs together (Figure 12b), or of the synthetic CSI value (Figure 12c). Further, in Figure 12d a focus on a single CPI is provided, with a view of the related extended attribute information in the object "property view". All the screenshots provided in Figure 12 represent the visual result of the introduction of the original smart objects (CPIs) into the realistic I-BIM environment and of their information enrichment by means of the original routines defined by the authors. Only the road and the terrain models and the external contexts are created using built-in functionalities.

Conversely, considering the approach discussed in Section 4.2, the pavement conditions can be analyzed in the design-oriented environment using the previously presented CSs. Again, original routines are required to import survey data from the external database for the various SIs and to calculate the consequent CSI values at each station.



(**a**)



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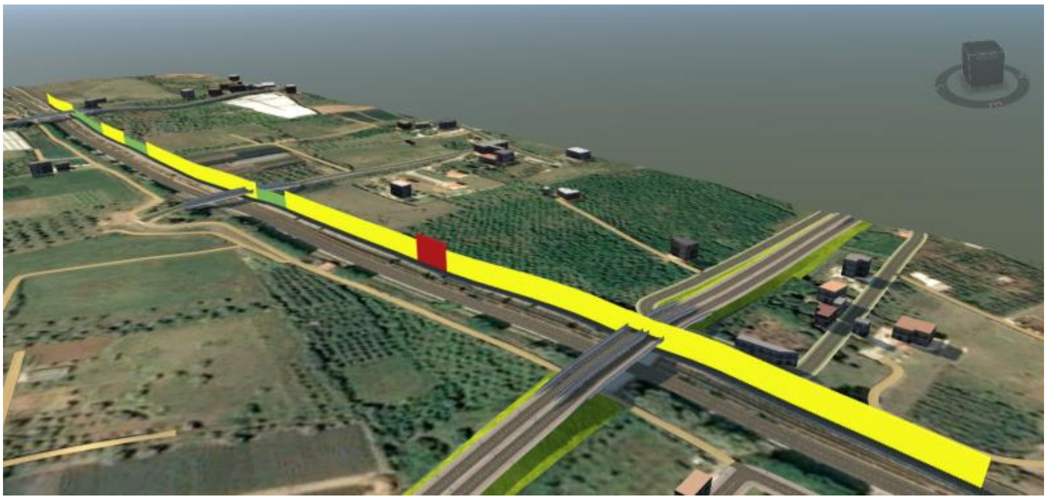
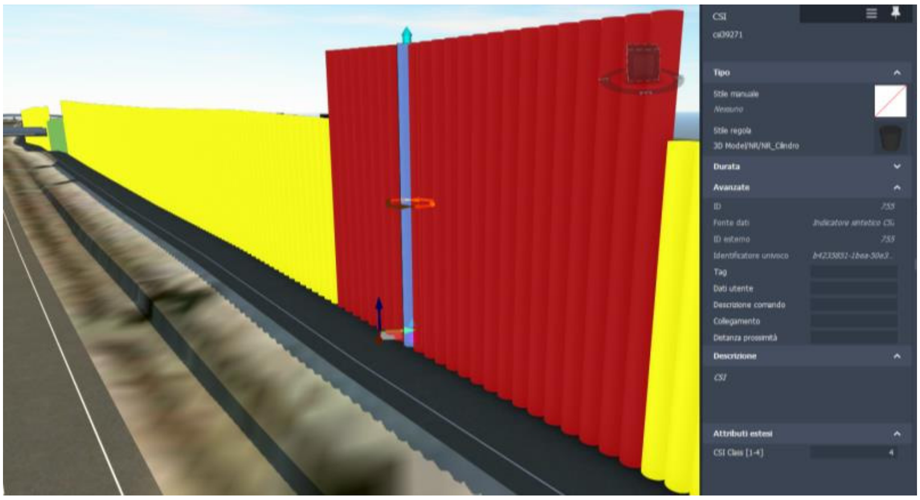


(**c**)

Figure 12. *Cont*.



(**d**)

Figure 12. Virtual inspection of the infrastructure pavement conditions in the I-BIM environment through the original CPI visualization: (**a**) example of IRI values; (**b**) example of 4 SIs with an example view of the original script used for characterizing the CPIs; (**c**) example of CSI values; (**d**) particular view of a single CPI for the CSI value with the related extended attributes.

Once the model is updated, analogously, the pavement conditions can be evaluated and analyzed within this I-BIM environment. This framework is beneficial not only for visualization and virtual inspection of the infrastructure but also for defining intervention types and producing the necessary rehabilitation design documents within the same operational environment. In this scenario, the virtual corridor, composed of various CSs, can allow for the assessment of pavement conditions and quality—measured by SIs and CSI—along the road alignment (Figure 13). This serves as a foundation for the intervention evaluation, but further processing algorithms can be implemented as decision support tools. As detailed in Section 4.2, different simplified intervention types were included in a reference catalogue and selected for each segment based on the critical conditions of SIs and CSI: the worse the indicator values, the more extensive the demolition and reconstruction intervention. This approach can be used to generate the necessary technical documents for maintenance and rehabilitation interventions, such as section views (showing also ex ante conditions and rehabilitation depth—Figure 14) or profile views (indicating rehabilitation depth for various pavement segments—Figure 15). The presented representations (to be complemented by quantity take-offs and other analytical reports and computations) are preliminary examples of the methodological approach. As these representations evolve and are enriched with state-of-the-art techniques, they can be used to precisely define the intervention activities.

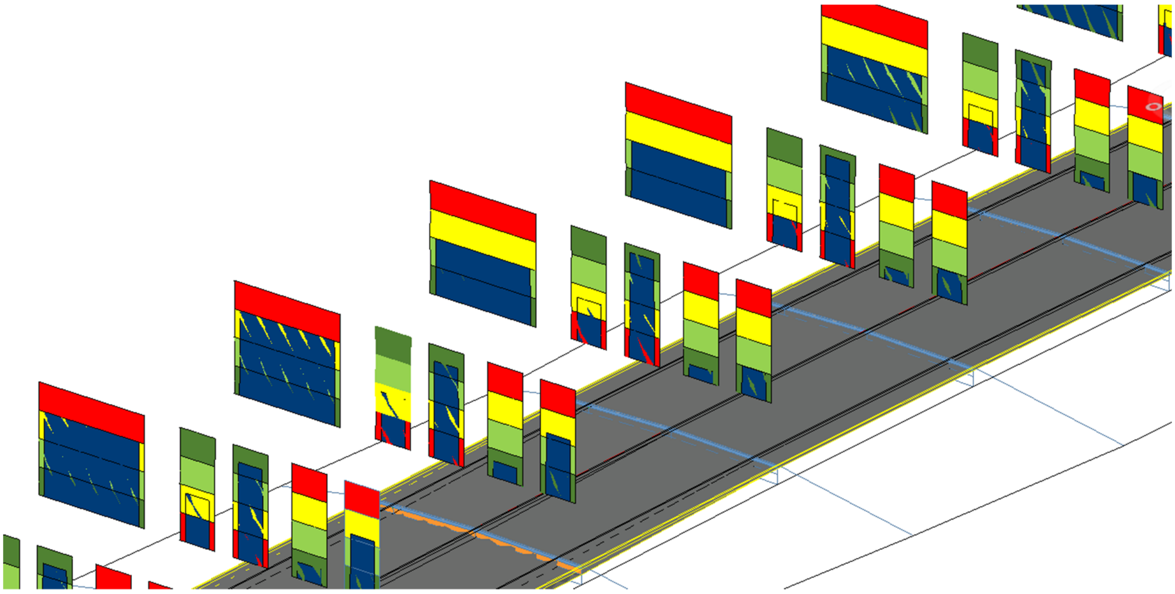


Figure 13. Graphical visualization of the pavement condition and quality at different sections (in terms of SI and CSI values).

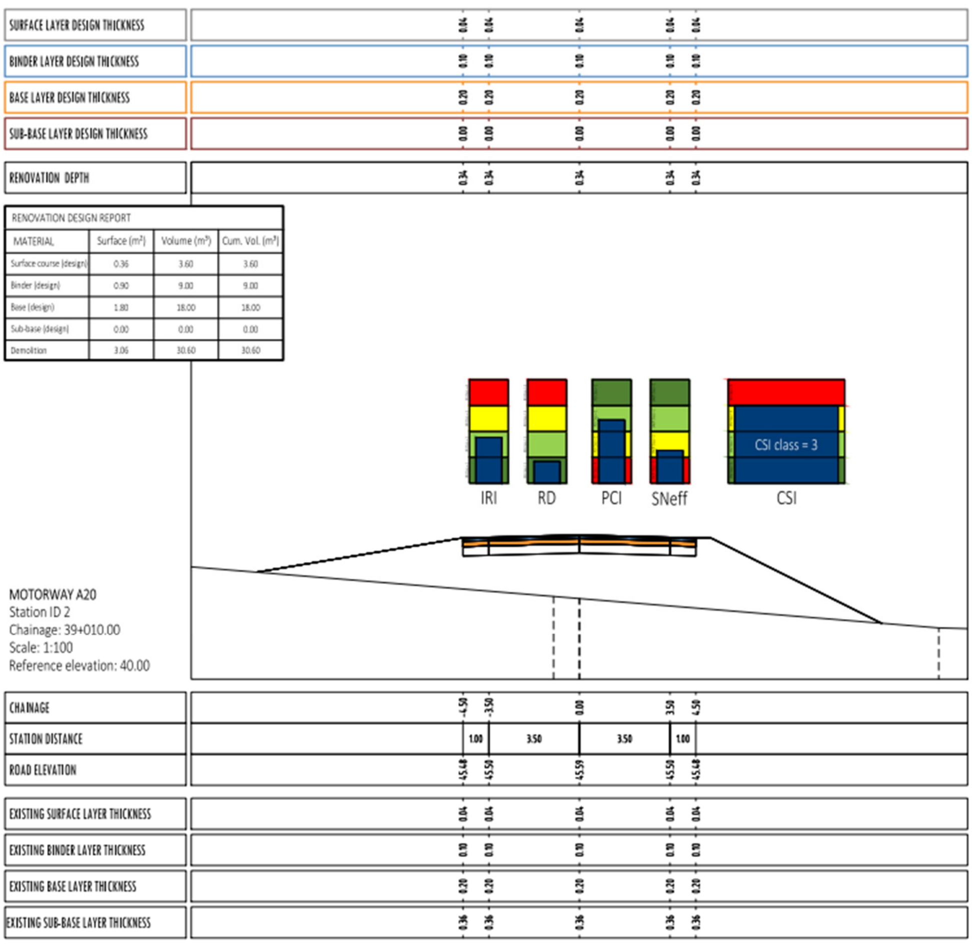


Figure 14. Example view of potential cross-section representation, evidencing ex ante quality levels of pavements and renovation intervention depth.

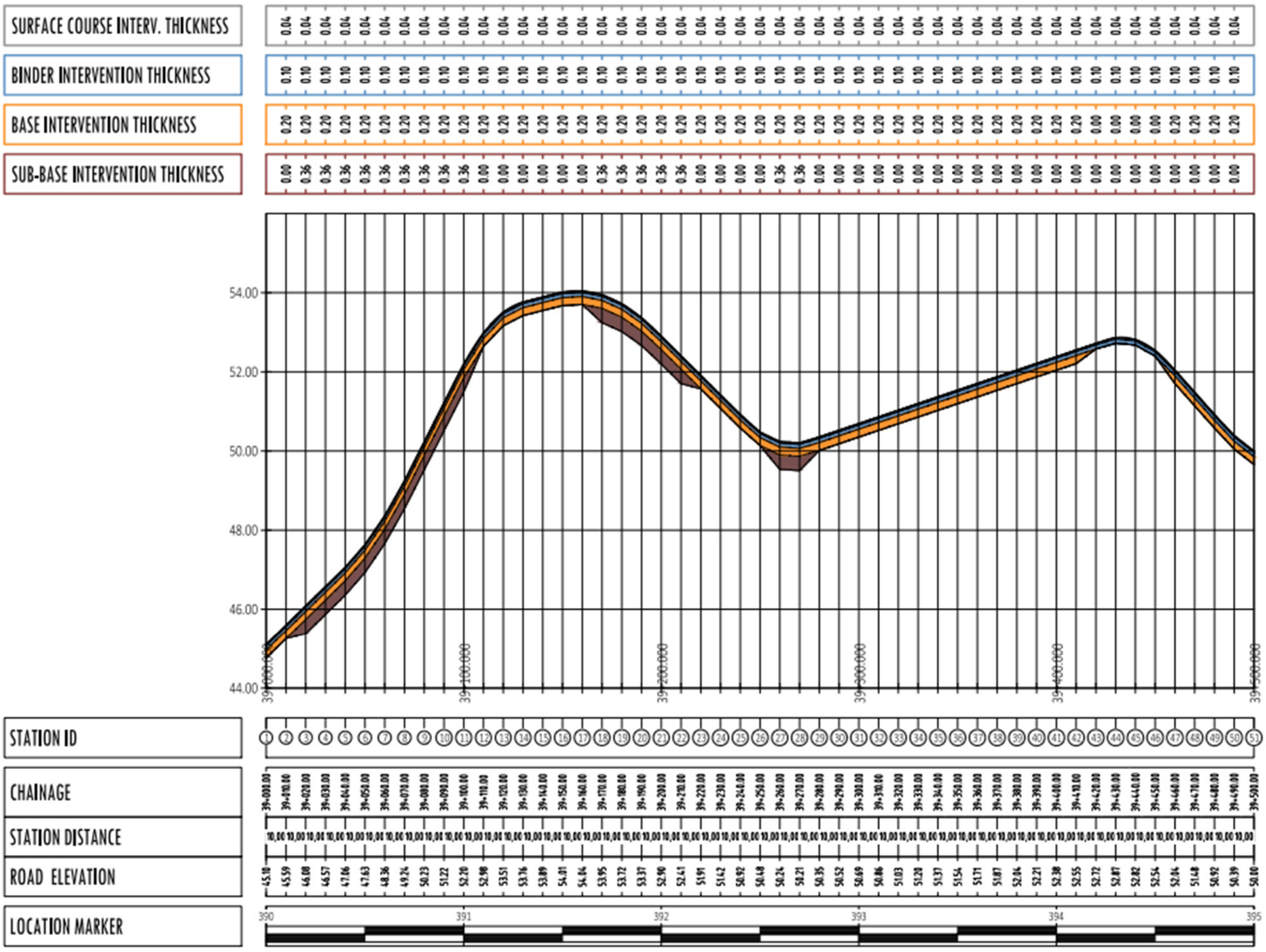


Figure 15. Example view of potential profile representation, evidencing renovation intervention depth (colored areas represent the different layer depth according to top legend and details).

6. Discussion

The examples presented in Section 5 regarded operative testing of the proposed procedural and methodological framework aiming to evaluate the implementation of road maintenance management processes in I-BIM environments by means of original solutions. As previously underlined, the proposed framework relies on currently available software tools but enriches them by introducing specifically customized smart objects and processing routines. It should be clarified that the research aim is not to modify existing theoretical and analytical standards and algorithms for maintenance management and intervention definition. Instead, the goal is to propose more efficient and up-to-date management platforms that can leverage BIM benefits for infrastructure maintenance. Currently adopted GIS solutions, despite useful for geolocating survey data on a network map, do not offer the operative and conceptual advantages of BIM approaches. This work evidenced potential solutions for asset virtual inspections in a realistic 3D environment and, most importantly, for performing maintenance and rehabilitation design steps in the same environment in which the operators can identify the pavement "health state". Traditional GIS platforms do not allow for the direct definition and production of tender and project documents, as they are not conceived for such purposes. Conversely, by exploiting the built-in design-related functions of BIM environments, operators can quickly and easily evaluate the segment conditions, identify the most suitable maintenance activities, and immediately design the interventions.

In this regard, the proposed frameworks have considered original solutions, scripts, and procedures, first, to import into the I-BIM environments survey data on pavement conditions. Then, they exploited visualization benefits and analysis opportunities of these platforms and created a unique operational environment directly linking the analysis steps to the detail geometrical design of the rehabilitation intervention. As previously mentioned, existing commercial solutions cannot directly store and process condition and maintenance-related information, since they lack adequate built-in solutions. Furthermore, they cannot offer specific processing procedures and algorithms for maintenance management purposes, which directly exploit input condition data and link them to maintenance and rehabilitation design steps. Consequently, this research provides an opportunity of improving the current approaches for extending the effective potential of BIM methodologies to the infrastructure sector.

In detail, two of the most popular software were selected and stressed with the introduction of original routines and solutions to handle maintenance information and variables. In both cases, it was possible to leverage the unique features of each software to develop convenient and useful BIM uses. In particular, the first application (Section 4.1) demonstrated the advantages of a realistic scenario for a more immersive inspection of the infrastructure useful to support base rehabilitation and maintenance decisions (Figure 12). On the contrary, the second framework (Section 4.2) offers greater data processing capacity and a more technical approach, up to the practical definition and design of an executive-level maintenance intervention (Figures 13–15). It is important to emphasize that, in both cases, the proposed processes were implemented in software tools primarily designed for the planning or executive design of new road infrastructures. This demonstrates that these environments can also be effectively used for setting up processes and operational flows oriented towards road maintenance management during operation.

A common feature of all the proposed processes is the continuous need for exchanging information and models between the two I-BIM environments, highlighting the need for the most advanced and coherent interoperability features. For some data and geometrical parameters, as shown, similar features are already available. In this perspective, the operative solutions proposed in this application are specifically defined to enable the two platforms to share the same type of information regarding pavement condition. This will allow operators to exchange data between different environments, bypassing the external survey dataset and adapting to the specific aims of the analysis, such as virtual inspection, data presentation, intervention definition, and proposal. Although specific routines for extended attributes data exchange have not yet been defined, the interoperability and coding opportunities offered by these environments make this approach effectively practical for future studies.

Compared to the most relevant previous studies, it is important to highlight that this research considered specific and dedicated I-BIM platforms, as in [15,33], excluding other BIM software (as in [16,32]). Furthermore, the proposed approach offers the possibility of storing and presenting data at a customized sampling scale, similar to what was presented in [15], rather than constant values for the entire road link, as in [33]. This increases the practical adaptability of the operative environment. Compared to the approaches presented in [15], this research introduces some strategical differences. First, it defines original virtual smart objects in both cases, specifically designed for storing and virtualizing road pavement conditions. Additionally, this work offers a completely different and more expressive 3D representation of road conditions in a realistic planning-oriented I-BIM platform. More importantly, by means of customized objects and original routines, the proposed approach is introduced in a design-oriented platform, providing all the advantages of accurate analysis and design, along with the possibility of directly defining all the required documentation for maintenance and rehabilitation project proposals.

Although some solutions are still embryonic, the research shows that, by further improving and extending the adopted approach, it is possible to envision an effective transition of PMS methodologies into better-performing and realistic I-BIM environments. This could close the loop in the life cycle management of the infrastructures, "from cradle to grave". Such an approach can also be leveraged to consider sustainability aspects related to the entire life cycle of the infrastructure asset. Properly handling pavement condition data, which strongly influence the overall sustainability of the road asset, is essential for optimizing maintenance activities and decisions, aiming to select efficient and sustainable solutions. According to some studies, albeit preliminary and partial, the adoption of BIM itself can contribute to decarbonizing the construction sector [37]. Moreover, the operative solutions can be specifically customized to account for life cycle assessment variables and impacts, as demonstrated in [33]. An operative I-BIM environment can be enriched to simplify comparisons of alternative maintenance solutions, facilitating impact comparisons and ultimately reducing resource and fuel consumption along with critical emissions.

Naturally, the overall vision required continuous improvements and enrichments before a full transition can become possible and practically adaptable. Considering the potential future developments of what is proposed here, the following themes can be identified among the many that can be envisioned:

- definition of a solid data interchange protocol with GIS environments to move coherently between network and project levels in maintenance activities;
- implementation of more advanced intervention criteria, with alternative possibilities for processing survey data according to their type, which varies from case to case;
- definition of chronological criteria to keep the information model updated as maintenance interventions are carried out;
- definition of processes for any plano-altimetric correction and adaptation to regulatory criteria in the case of interventions during operation;
- implementation of processes that take into account the disturbance caused to road traffic by maintenance activities with traffic simulations.

Finally, considering potential limitations in the scalability of the proposed approach to wide infrastructure projects, it is fundamental to identify elaboration and real-time processing issues that arise for very extensive networks. The proposed solutions should act at different scales, in compliance with the peculiarities and intrinsic characteristics of the various operative environments. On one side, the approaches described in Section 4.1, involving a realistic planning-oriented I-BIM environment, are useful at an intermediate level between network and project scale. According to the previous considerations, an exhaustive GIS/BIM integration can be very productive, accounting for their different features and peculiarities related to their natural scales of representation and detail content [38]. Traditional GIS solutions should be used at the network scale for comprehensive network condition visualization and budget prioritization. Moving to the next level, the realistic virtual inspection of the single road link, at an intermediate scale, exploits the proposed solutions (in 3D) or other plan and color-based representations. A similar integration was proposed and discussed in [30] for construction quality-related issues. Finally, the analysis at the project level, on a reduced length, should be performed in a design-oriented I-BIM environment, relying on the proposed approaches. Once the budget is assigned, in the related framework the operator can evaluate the effective condition of the pavement sections, select the most convenient interventions, and produce the required tender documents.

7. Conclusions

In this paper, the authors investigated BIM uses related to infrastructure maintenance management in customized and optimized I-BIM environments to test the potential benefits. By processing information derived from detailed pavement condition surveys on site, the authors have defined operative frameworks in two different I-BIM environments to improve data analysis visualization, allow execution of virtual inspections, and define rehabilitation interventions in more user-friendly and immediate ways than current practice. Original virtual smart objects, representing the "containers" of the survey information, were defined in different environments. Then, they were adapted to display efficiency and quality levels of the pavement segments by using original routines coded to automatically import survey data from external datasets. The case study, referring to a motorway in Sicily, evidenced the effectiveness and the potential benefits of a similar approach that ensures increasing productivity and potential error reductions for road agencies.

The proposed original approaches can extend the potential of currently available platforms not originally designed for and adapted to handle and process pavement condition data. The proposed virtual smart objects, their related attributes, and the original routines can provide specific solutions to handle maintenance management issues in I-BIM platforms. The overall approach may be helpful in defining more comprehensive frameworks that can effectively overcome typical operative and management issues of traditional PMSs. As evidenced by the presented case study, BIM can effectively contribute not only to design and construction phases but also to maintenance management by simplifying the analysis of condition information in a realistic environment and allowing a comprehensive platform for condition analysis and intervention design. Obviously, although the preliminary combination and decisional algorithms—used in this context only for testing the overall methodological framework—must be improved according to state-of-the-art solutions derived from robust methods currently applied in the PMSs, the convenience of a similar transition appears now clearer. Finally, such an evolution for BIM platforms can simplify the expected transition towards a full management of all the project phases in BIM, as defined by current European and national policies and regulations.

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