Received: 14 April 2025 | Revised: 10 September 2025 | Accepted: 25 September 2025 | Published online: 12 December 2025

RESEARCH ARTICLE

Journal of Computational and Cognitive Engineering
2025, Vol. 00(00) 1–13
DOI: 10.47852/bonviewJCCE52025931

BON VIEW PUBLISHING

Semantic-Driven Automation of BIM for Stone-Paved Roads: An Ontology-VPL Integrated Approach

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Abstract: The integration of semantic technologies and procedural automation is redefining how infrastructure assets are modeled and managed. Yet, stone-paved roads, common in historical urban centers, remain largely unsupported by existing building information modeling (BIM) standards and tools. This paper presents an innovative, fully automated workflow that bridges this gap by combining a visual programming language (VPL) approach with an ontology-driven semantic framework. Compared to the traditional manual modeling workflow in the BIM-Authoring software Autodesk Civil 3D, which may take several hours, the proposed method generates a complete 3D BIM model by fully automating several modeling operations via a Dynamo graph that takes very short computational times. To achieve this, we developed a parametric modeling pipeline that, based on structured input data, can rapidly generate high-fidelity 3D models of stone-paved roads. To overcome semantic limitations in the Industry Foundation Classes (IFC) schema, we introduce the IFC for stone-paved roads (IFC-SPRO) ontology, designed to enrich geometric models with machine-readable knowledge about modular pavement typologies and maintenance strategies. By converting IFC data into resource description framework (RDF) format and querying it via SPARQL and AI-driven interfaces, the model supports advanced information retrieval for asset management and heritage conservation. The proposed approach not only enhances interoperability and reduces modeling time dramatically but also establishes a scalable foundation for integrating historical road infrastructure into modern digital workflows.

Keywords: BIM, visual programming language, ontology, Civil 3D, Dynamo, SPARQL Protocol and RDF Query Language

1. Introduction

Building information modeling (BIM) is a methodological approach for creating and embedding data within the model elements of an engineering asset. This approach facilitates better management of information throughout all phases of the asset's life cycle. It involves the use of several information technologies (IT) for geometric and semantic modeling, to manage projects and share the models on cloud platforms [1]. A BIM model is a multidimensional representation of a building or an infrastructure with up to seven dimensions: 3D for geometry; 4D for scheduling simulation; 5D for cost evaluation; 6D for environmental, economic, and social sustainability; and 7D for facility management, maintenance, and disposal [2].

Throughout the entire building life cycle, from conceptual design to construction and facilities maintenance, the information of a BIM model can be used to support decision-making [3]. BIM may incorporate other planning and project management approaches into its methodological framework, maximizing the potential of both [4, 5]. Researchers have long been exploring the potential benefits of BIM for cost estimation [6], sustainability [7], and facility management [8].

By definition, BIM is a multidisciplinary methodology in that there is a multitude of software and applications that fit into BIM workflows. Standard file formats are therefore needed to allow interoperability between these IT tools; otherwise, the transmission of information between project stakeholders and thus the success of the methodology itself would be compromised. A widely adopted file format for BIM software interoperability is called Industry Foundation Classes (IFC), which is a registered platform-neutral open-source standard. IFC was created and maintained by buildingSMART, which is a global organization of chapters, partners, and sponsors, focused on solving industry interoperability problems.

Going far beyond the three-dimensionality of spaces and geometries, BIM covers many fundamental aspects through semantic modeling,, for example, the retrieval of design data or the current state of the asset and the inference of new information from the data stored within the model, through rules and relationships.

2. Literature Review

Ontology refers to a semantically structured description of concepts and their relationships. In the field of computer and information technology, ontology is a representation vocabulary and the conceptualizations of the terms it contains, frequently tailored to a particular area or subject matter [9].

Ontologies can be utilized to address BIM interoperability problems, since it is possible to operate ontologies within IFC schema, by means of the IFC Web Ontology Language (ifcOWL). The OWL technology offers an alternative to concept libraries by providing opportunities to connect the IFC schema with other BIM standards and standards from other disciplines in a straightforward manner [10].

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BIM for Infrastructure (I-BIM) represents BIM declination for roads and transport infrastructure. It can entail modeling of all sub-service facilities and plants and applies to both roads and railways [11].

BIM and I-BIM share the purpose but differ methodologically insofar as the works to which they relate differ. Architectural works generally have a smaller spatial footprint than road and railway work, which can extend over several kilometers. Furthermore, the three-dimensional orientation of road axes is such that the use of horizontal reference planes is not appropriate, as in the practice in architectural BIM.

For linear infrastructures, one resorts to procedural modeling, whereby consequential modeling phases produce the elements in a hierarchical relationship: terrain, planimetric alignment, vertical profile, 3D axis, 3D solids. Many academics works have dealt with I-BIM, for railways [12], for airport infrastructure management, and in particular for runway pavement maintenance [13, 14], for bridges [15], tunnels [16, 17], ports [18], and canals [19], as well as for earthworks, as levelling, embankments, and overburdens [20]. I-BIM applications are particularly effective when coupled with innovative data management methods, such as the Internet of Things (IoT), enabling intelligent transport system (ITS) implementation [21]. Very promising is the use of machine learning [22]: Jha [23] used machine learning-powered algorithms to index pavement conditions and apply predictive analysis on its deterioration.

I-BIM has been tested in academic research for as-built models of roads for design optimization [24] or to review and carry on analysis on the status of road pavement [25]. I-BIM can be a powerful pavement management support tool, in both urban and suburban settings. For example, I-BIM and GIS have been integrated within the same framework for technical–economic analyses and maintenance planning [26, 27].

BIM is based on procedural parametrical modeling to make models dynamic. It means that by modifying one parameter, the whole model adapts according to the rules that involve that parameter. It involves defining the geometry of the model through a system of mathematical relationships between variables and parameters and enabling the model to be updated in real-time as these parameters change [28, 29].

Software for the geometric modeling of roads typically works by implementing three-dimensional axes along which a geometry, the cross-section, can be extruded to create the physical road. This has several restrictions, especially when it comes to more complex construction components like safety barriers, hydraulic systems, technical installations, and furniture, that are nonetheless essential components of the infrastructure. An example is the work of Zhang et al. [30] for modeling retaining walls and safety barriers in an attempt to compensate parametric object libraries used for modeling, which are frequently inadequately provided.

One way to extend the geometric modeling potential of BIM is to use algorithmic methods developed by experienced users. An approach for developing algorithms with basic computer skills is visual programming language (VPL).

VPL enables programmers to construct the logic of their programs using visual elements like blocks, flowcharts, and graphs rather than written text [31]. In their 2021 article, which provided an in-depth review of the state of the art on the use of VPL associated with BIM in application to the world of infrastructure, Collao et al. [32] pointed out that although the use of this tool is growing in popularity in the architectural domain, this does not hold true for infrastructure projects.

Grasshopper and Dynamo, which are respectively tied to Rhinoceros by Robert McNeel & Associates and Revit/Civil3D by Autodesk, are two of the most popular visual programming language tools for Architecture, Engineering, Construction, and Operations (AECO) applications.

In 2023, Kossakowski [33] leveraged the potential of visual programming in structural design. In the same year, Roman et al. [34] used VPL to enhance automation in Scan-to-BIM processes. Instead of utilizing conventional Civil 3D modeling tools, Tang et al. [35] in 2020 established a subroutine in the Python programming language, within Dynamo, to do the structural analysis of a road pavement generated using Dynamo. In this study, the potential for directly employing visual scripts to parametrically represent a road solid is investigated.

These works demonstrated the promise of VPL while also highlighting some of the drawbacks of software when used to model and share road infrastructure projects in a BIM setting. The main limitations are due to interoperability, but especially to the IFC schema that needs to be improved for specific assets, as in the case of stone-paved roads.

Stone-paved roads often have historical value as part of historic city centers. An example of an application in this field, with the integration of I-BIM and Heritage-BIM (H-BIM), is the case study by Biancardo et al. [36], which involved the realization of an as-built model of a main street in the historic center of Naples (Italy), by combining several software tools and using advanced surveying techniques, such as laser scanning and photogrammetry. Other cases of using BIM on stone roads refer to Archaeo-BIM, as they are found in the archaeological site of Pompeii [37, 38].

In this context, although in recent years buildingSMART has been working on the extension of the IFC format for roads, as well as for railways, tunnels, bridges, and ports, the scheme does not provide specific classes for roads with modular pavements that involve a wide variety of construction techniques, materials, and other intricate characteristics, such as historicity.

A specific ontology for stone-paved roads can support three possible applications: (i) integration – the ontology provides a common base of knowledge by precisely defining concepts and relations; (ii) data validation – the ontology constitutes a tool to easily validate data against the definitions provided by the ontology itself; or (iii) inference – the ontology allows for the machine to read the data and to retrieve new information [39, 40]. The first use accomplishes what is defined by Bloch [41] as semantic enhancement, which is a process for the integration of IFC with external data sources for the improvement of the schema, while the second and especially the third relate to what Bloch defines as semantic enrichment. To date, there have been several studies that have delved into the subject of ontologies dedicated to the road environment. For instance, Fernandez et al. [42] created an ontology for intelligent transportation systems utilizing a traffic sensor network in 2016 and Houda et al. [43] created a public transportation ontology in 2010 to enable user journey planning. The development of the Ontology-based Traffic Accident Risk-Mapping (ONTO_TARM) ontology by Wang and Wang [44] for risk mapping and the VEhicular ACcident ONtology in OWL data representation by Barrachina et al. [45] for the simulation of vehicular crashes demonstrate some interest in the field of road safety. Researchers dealt also with ontologies for risk assessment [46], road crash injuries estimation [47], vehicular traffic information management [48, 49], and travel and disruptive events impacting transport systems modeling [50].

The aim of this research article is to investigate an integrated approach in BIM by exploiting VPL for geometric and semantic modeling and ontology for semantic enhancement. The aim is also to highlight the need to address modular stone roads, which are common historical infrastructures and often involved in extensive extraordinary maintenance projects in historic city centers. Indeed, both from the standpoint of VPL-based procedural modeling and from the standpoint of semantic improvement, there is a glaring lack of commitment to stone-paved roads. To date, stone-paved roads have been modeled using horizontal extrusion techniques, followed by the application of a texture to the top surface. This approach ignores the benefits that a more detailed representation could provide, such as the ability to simulate the interaction of loads with particular layouts, operation, and maintenance strategies.

3. Research Methodology

In the current research work, an integrative approach was pursued between I-BIM, with procedural modeling innovatively completed in VPL, and semantic enhancement of the IFC format through a dedicated ontology.

This section is divided into subsections, beginning with a description of the baseline methodology for modeling in BIM, to base the comparisons in the discussion of the results.

The proposed methodology is described in the following subsections: Research design, Dataset definition, 3D Modeling, 7D Modeling, and Semantic Enhancement.

3.1. Baseline methodology

The 3D modeling of road infrastructure differs from that of buildings in that geometry has a preponderant dimension over the other two. Therefore, they are referred to as linear infrastructures. The principles by which modeling software operate are therefore radically different. Specifically, the 3D representation is primarily created through the extrusion of typological cross-section(s) along a 3D axis, which can be achieved in several ways. Conceptually, it involves coordinating the horizontal spatial orientation (the planimetric layout) with the vertical orientation (the vertical profile). The linear BIM modeling procedure can then be divided into the following steps, corresponding to digital terrain model (DTM), horizontal alignment, vertical profile, cross-section typological section, corridor, and 3D solids.

In the present research, the horizontal alignment consists of straight sections that are connected with curves of constant radius and curves of variable radius (spirals). The road layout thus made has a two-dimensional orientation; the elevation is zero. Projecting the layout onto the DTM produces the vertical profile of the terrain, the starting point for drawing the design vertical profile. In analogy with the horizontal alignment, the vertical design profile consists of straight sections, with constant slope, connected with curves of various types (parabolic, circular, asymmetric, etc.).

The typological cross-section is made in a variety of ways. Generally, objects found in libraries are assembled, for example, layers of road pavement and edge elements such as curbs, gutters, sidewalks, safety barriers, any traffic dividers, and embankments. The elements of the cross-section are defined by points, the links that connect them, and the shapes that are enclosed by them, all of which are appropriately coded. These elements can be customized using different applications, meaning that existing default libraries can be extended, or new ones created from scratch for the specific project needs.

Once the typological cross-section, horizontal alignment, and design vertical profile are ready, the corridor can be created, the 3D modeler obtains its baseline by associating the dimensions of the design vertical profile with the horizontal alignment and generates the extrusion. This extrusion is done by connecting the encoded points of the assembly positioned along the 3D axis at a step defined by the "frequency" parameter of the corridor.

Solids can be extracted from the corridor and used for various applications including volume computation and export to IFC.

The most basic methodology for BIM modeling is a sequence of operations to be manually performed according to the commands, options and settings of the software in use. The computational overhead is relative to the size of the project and thus to the amount and type of data: Is the survey a point cloud? If so, how large?

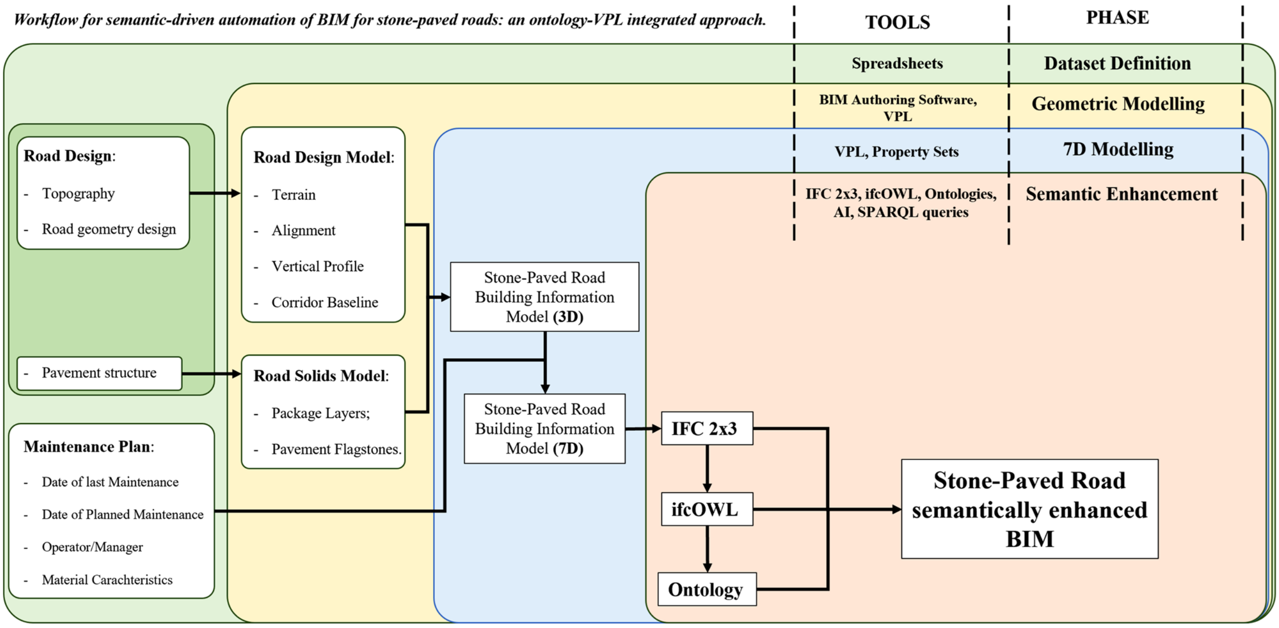
In terms of time, on the other hand, the onerousness is related both to the experience of the operator himself and to the inherent characteristics of the software, for example, how user-friendly it is: in general, it can be related to the number of clicks and inputs. The number of clicks, inputs, and thus the complexity of the commands increases the probability of error, the need to rework, and of producing inaccurate models.

The methodology that this paper proposes intends to be an evolutionary step toward a simpler and more controlled way of working through two key concepts: parameterization and automation.

3.2. Research design

Figure 1 presents the graphical abstract of the four-phase methodology applied.

Figure 1
Graphical abstract: methodology



Phase 1 consists of compiling the spreadsheet that has been specially designed for this application. This constitutes the starting dataset and contains the geographic coordinate lists of points that will be processed by the software to produce the topographic surface. The dataset also contains the design parameters of the road layout, the dimensions of the cross-section, and the maintenance plan.

Phase 2 corresponds to geometric modeling according to the BIM methodology. The entire modeling process was completed using the Dynamo add-on for Autodesk Civil 3D BIM Authoring Software and its VPL Environment (VPLE). In order to create the road geometry (including the digital terrain model (DTM), the alignment, the vertical profile, and the corridor baseline), data pertaining to topography and road geometry parametric design, including lengths, curve radii, spirals parameters, and singular points geographic coordinates, have been extracted from the spreadsheet. Similarly, pavement structure data, such as layers thicknesses and pave geometry were used for road solids modeling. The deployment of the road flagstone solids along the baseline of the corridor resulted in the creation of the final 3D model of the stone-paved road, bringing the second stage of the workflow to an end and ushering in the semantic enhancement stage – or Phase 3.

The 3D model now includes information on the maintenance schedule, which is a particular BIM application in what is referred to as the seventh dimension of BIM. Property sets were made from the data in the spreadsheet and then correlated with the solids of the 3D model, making it into a 6D model, with the express intent of completing or at least enhancing the information content of the model.

The semantic enhancement of the model occurs in Phase 4: the model has been exported in IFC 2x3 format, converted to ifcOWL, and then into an ontology that has been modified using Protégé [51] software to create new ontology for stone-paved road maintenance reasons. Finally, the ontology was tested thanks to a SPARQL Protocol and RDF Query Language (SPARQL) carried out with an artificial intelligence (AI) large language model (LLM).

3.3. Dataset definition

The dataset was organized in a spreadsheet that can be recalled in the algorithm as comma separated value (CSV) format or as Microsoft Excel spreadsheet. The data are related to the basic modeling of a road, for topographical context, planimetric alignment, vertical profile, and road section.

In this phase, the research tests the proposed methodology by applying it to a structured dataset, with the goal of validating its capacity for automated BIM modeling. For this reason, the testing dataset is synthetic, while a real-case study is considered at a later stage (Section 4).

To model the topography, a "DTM PENZ" sheet was created, organized in four columns: ID, Easting, Northing, and Elevation. Therefore, 100 spatial coordinate points were defined within a predetermined numerical range: 0–100 for easting and northing and 0–10 for elevation were used to imitate topography.

A straightforward layout made up of two tangents connected by a fixed-radius curve was simulated for the alignment. A variable radius curve was not considered because it is typically not present in historic stone-paved roads. To define the elements of the alignment, it was necessary to identify the coordinates of the end vertices, two for each tangent, and the radius of the curve. From these few inputs, the software can create an alignment composed of tangent–curve–tangent. For the vertical profile, a course consistent with the alignment was assumed: a point was identified at the center of the curve to define a cusp in the vertical connection linking two slopes, the first starting at the initial point of the first tangent and the second ending at the second end of the second tangent. The data for modeling the road cross-section are the thicknesses of the three layers that were assumed to make up the road package and the three dimensions of the single flagstone.

The dataset also covers road maintenance data. In particular, the sheet name is "Properties" and has three columns: Property Set Name, Properties Name, and Properties' Value. The following properties are listed: last maintenance date, planned maintenance date, person in charge of maintenance operations, and then data on mechanical behavior, such as type of material, material origin, compressive strength, and tensile strength.

3.4. 3D modeling

The modeling was performed completely within Dynamo. VPL is based on graph theory, consisting of nodes (which contain instructions) and connectors (which link nodes to form an input–output relationship). There are three types of nodes: constructor, which is used to create new entities, whether geometric, mathematical, or properties; functions, which are used to modify entities and create interactions; and properties, which query entities.

The modeling process for geometric and semantic modeling is shown in Figure 2.

Reading it from the left to the right, the first group of nodes collects user input, namely the path to the text file in .csv or .xls format. This file contains the following data: coordinates of the geographical points that triangulated will result in the DTM; coordinates of the geographical points that represent the notable points of the road layout geometry; and geometry and dimensions of the cross-section components.

Next, the first four groups of nodes in gray proceed to reprocess the information in the sheet, extracting the data, reorganizing it into lists, and applying the necessary filters. The first two select the sheet of the excel document, separate the headers from the numerical data, flip the data lists, and then separate the coordinates x, y, and z that stand for Northing, Easting, and Elevation, respectively. Likewise, the other two groups of nodes extract the cross section and the maintenance plan data. Then, in orange are the groups of nodes that realize the modeling of the DTM, alignment, and vertical profile. To begin the DTM modeling process, the algorithm first creates Coordinate Geometry (COGO) points—intelligent objects that are handled inside Civil 3D and include coordinates and other information—from the coordinates extracted previously, and then it creates a triangular irregular network (TIN) surface, as the DTM. For the alignment modeling, another list of point coordinates is used to draw an AutoCAD polyline that can be directly transformed into an alignment.

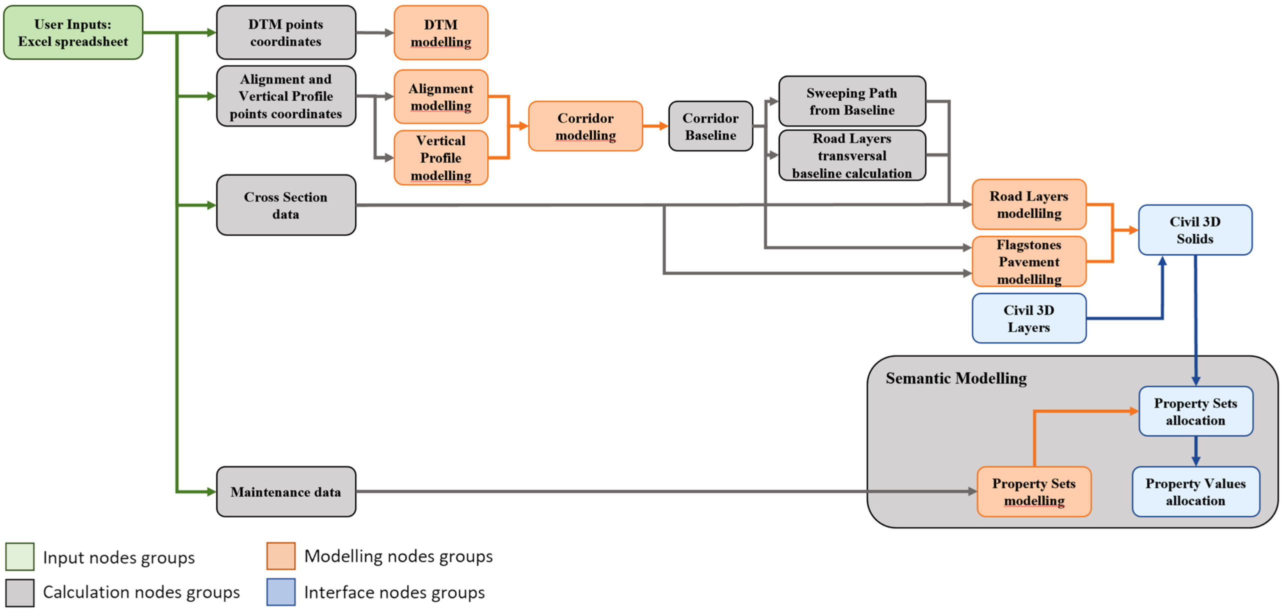
The vertical profile is created starting from the alignment, and only in a second phase, the elevation is added to its tangents vertexes.

Next step, the corridor is modeled, and its baseline, which coincides with the road axis that coordinate alignment and vertical profile, is extracted. The algorithm produces a Dynamo geometry from the baseline to provide a path for the geometry obtained from cross-section data to be extruded. These solids, together with the flagstone solids, constitute the 3D model.

The sweeping path is created as a Non-Uniform Rational B-Spline (NURBS) curve, inferred from a Dynamo polycurve that is based on a list of points selected on the Corridor Baseline thanks to a range (i.e., a list of values defined by a step between a start [the baseline starting station] and an end [the baseline ending station]). Another group of nodes deals with the cross-section transversal baseline calculation based on the coordinates of two points belonging to the baseline. To model the road layers, cross-section data are used in mathematical relations as modeling parameters.

Therefore, proceeding to the right, the other two orange groups of nodes oversee the road package solids modeling according to the boundaries representation (B-REP) approach, which models a solid

Figure 2
Dynamo workflow



from shapes defined by edges defined by vertexes. The computation of eight points, listed from A to H, grouped to form the vertices of three shapes whose edges are specified by polycurves made using the nodes PolyCurve.ByPoints, is contained in the code block (Figure 3). The solid geometry of the road layers is then created by sweeping the polycurves across the route provided by the baseline's NURBS curve.

Following, the points coordinate values are reported:

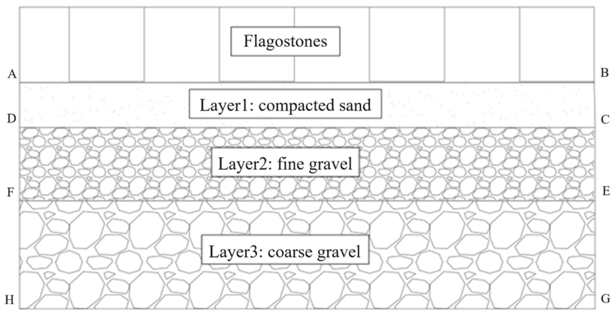
1) A is the starting station of the corridor baseline;
2) B is taken as offset from A complying with the lane width parameter;
3) $C_X = B_X$, $C_Y = B_Y$, $C_Z = B_Z - L_{1T}$;
4) $D_X = A_X$, $D_Y = A_Y$, $D_Z = A_Z - L_{1T}$;
5) $E_X = B_X$, $E_Y = B_Y$, $E_Z = B_Z - (L_{1T} + L_{2T})$;
6) $F_X = A_X$, $F_Y = A_Y$, $F_Z = A_Z - (L_{1T} + L_{2T})$;
7) $G_X = B_X$, $G_Y = B_Y$, $G_Z = B_Z - (L_{1T} + L_{2T} + L_{3T})$;
8) $F_X = A_X$, $F_Y = A_Y$, $F_Z = A_Z - (L_{1T} + L_{2T} + L_{3T})$.

where L_{nT} stands for the n^{th} layer's thickness.

The algorithm's last stage involves modeling and placing the flagstones.

Each flagstone is represented mathematically as a cuboid, a solid with dimensions determined by its width, length, height, and origin. The placement logic is to create a grid of points, each of which is the origin of a cube (i.e., a single flagstone). The grid is determined by offset, elevation offset, and station parameters, starting from the corridor baseline data. The offset is coherent with the baseline x-axis, the station with the baseline y-axis, and the elevation offset with the baseline z-axis, considering a local coordinate system (CS) coherent with the baseline. The offset range start is defined as start + x/2, where start is the baseline start station and x is the sum of the flagstone width and the joint width. The end is specified as lane width, which is the lane width, and the step is defined as x. The station is determined as a range of values: the start is determined as start + y/2, where y is the total of the joint and flagstone lengths, end is the baseline end station, and step is y. Half of the flagstone height is used to compute the elevation offset.

Figure 3
Road layers solids: cross-section scheme with points coordinates



These data are given as input to obtain the grid of points. The algorithm also creates a CS for each point so that the solids can be oriented according to the baseline path.

The last stage in the geometric modeling process in Dynamo is to convert the developed proxy geometry into an object that can be seen and controlled in the Civil 3D user interface. The geometry must be addressed to a Block in the model space. The geometry must be addressed to a Block in the model space which is based on the existing document. Therefore, the solids of the road layers, the solids of the flagstones, and the open file the user is working on are the inputs of the last set of nodes called Civil 3D Object Creation, which convert the proxy geometry into AutoCAD Civil3D objects by accepting a layer, a block, and the geometry as input. This leads to the creation of distinct layers for each road component: "L1," "L2," "L3," and "Flagstones."

3.5. 7D modeling

The portion of the workflow needed to represent the data arranged in Civil 3D's so-called Property Sets is grouped in gray in the right corner of Figure 2. The road solids (flagstones and layers 1, 2, and 3) and the data for the property sets (property set names, property names, and property values) are given as input to a group of nodes that deals with the generation of Property Sets. These are lists of information that Civil 3D can recognize and correlate with things like solids. These lists are originally empty; that is, they just include the names of the properties, but not their values. The target solids are then associated with the property sets that were formed by the other two groups of nodes, which subsequently populate these property sets with the required data.

3.6. Semantic enhancement

Following the geometry and information modeling phase, the model was exported to IFC 2x3 format. Subsequently, the file was recorded and converted into Terse RDF Triple Language, .ttl (known as Turtle) format. This is a logic-based format to represent the ifcOWL scheme and thus allows Semantic Web (SW) technology to be exploited. Thanks to the work of Pauwels and Terkaj [52], who developed a tool based on EXPRESS schema for converting IFC models to ifcOWL representations, it was possible to convert the IFC 2x3 model to ifcOWL and then exported to the Turtle format. The Turtle model is a semantic model (ontology) of the IFC road model. The ontology contains individuals, or instances with the common IFC values (e.g., enumerations, materials, styles), and geometrical information of the objects modeled (e.g., locations and dimensions).

The transformation from the information model to the semantic model has many applications in knowledge engineering thanks to semantic web technologies. A simple application is to query the semantic model using SPARQL, a RDF based semantic query language, for retrieval of knowledge objects. This is, however, nothing more than querying information models using modern object-oriented programming languages, like Python. The real value of semantic models is demonstrated by semantic reasoning using reasoning engines, which are usually built in semantic tools like the software Protégé, an open-source ontology editor and framework for building intelligent systems. Semantic reasoning can be used for validation of instance semantic models (as in the present study). A common use case is to have another validation ontology (or domain ontology) that contains concepts, objects, and data relations and rules (i.e. SWLR - Semantic Web Rule Language Rules) that are then used for validation of the instance semantic model.

To create the validation ontology (domain ontology) following development, we considered (i) specification to determine the ontology scope, reflected by the name of the ontology; (ii) acquisition phase, in which knowledge sources are collected to build concepts and relationships; and (iii) formalization where the taxonomy and the lexical term are defined for the final hierarchy [53]. The resulting ontology contains conceptualizations as well as instances (individuals) being a domain specific application ontology. The validation ontology was designed for roads and specifically for stone-paved roads, the Stone Paved Road Ontology (SPRO). It also contains specifications for maintenance works as reported by de Oliveira et al.'s work [40]. Subsequently, the SPRO ontology was used to validate the instance ontology in the .ttl format. The validation results are usually proof of semantic compliance followed by semantic reasoning (i.e., road complies with building permit rules).

The ontology was then put to the test using a SPARQL query. The query was used to access and modify data that has been saved in Resource Description Framework (RDF) format. RDF is frequently used in ontologies and semantic web applications to describe data. One must have access to an RDF triple store that houses the ontology data to run a SPARQL query on it. The subject–predicate–object triple format is used in the triple store, a database created specifically to store and handle RDF data. Querying mechanisms can be applied to retrieve information based on the focus of the ontology itself. In the case of this study, the query is about planned maintenance intervention dates and actors involved.

4. Real-Case Scenario

To evaluate the applicability of the proposed methodology in a real-world scenario, a test case was developed using Poštna ulica, a historical pedestrian street located in the city center of Maribor, Slovenia. The road, approximately 110 meters in length, is characterized by a continuous longitudinal slope of 2% and paved with porphyry cubes arranged in staggered rows. The street features a simple cross-sectional profile with a central pedestrian lane flanked by flat sidewalks on both sides, resulting in a uniform transverse geometry.

The purpose was to construct a medium-detail as-built model aimed at supporting maintenance simulation within a 7D BIM framework. The input dataset was extracted using publicly available mapping services integrated into Autodesk tools (Bing Maps), allowing for the acquisition of geographical coordinates. These were structured into a Microsoft Excel file replicating the format used in the synthetic dataset described earlier. The spreadsheet included spatial coordinates for DTM generation and 3D feature lines, along with maintenance-related data.

5. Results and Discussion

The first result that can be appreciated is the graphic visualization of the BIM model of the road, obtained according to procedural parametric design. Figure 4 illustrates the result obtained from the script described in the methodology with a single click. Computation times are very short (less than 30 seconds), excluding data preparation time.

The Poštna ulica model, including DTM, alignment, profile, corridor, and manual insertion of modular paving, was realized according to the baseline methodology in 3 hours circa, based on the experience of a certified BIM Specialist for infrastructures according to the UNI EN ISO 11337-7. This stands in line with the estimation based on scientific literature by Agustian et al. [54] and on the experience shared by users on technical online forums.

In contrast, the proposed automated method promptly executes the VPL-based algorithm for the full geometric modeling process on a standard workstation: GPU Intel(R) UHD Graphics 1.1GB, RAM 16 GB, Intel(R) Core (TM) i7-10875H CPU 2.30 GHz; SSD 1 NVMe PC711 NVMe SK Hynix 512GB, SSD 2 NVMe PM9A1 NVMe Samsung 1024GB.

The proposed method represents an improvement of the manual methodology in terms of computational time. Moreover, it makes the result less dependent on the operator's skills. Modeling repeated modular elements in large numbers is a highly unprofitable operation to undertake manually and it can lead to additional mistakes,

Therefore, automation is the most straightforward solution.

Table 1 reports the KPIs for comparing the methodologies, broadening it beyond computational time.

In addition, successful export to IFC ensures that the model can be viewed in visualization software, such as the open-source Open IFC Viewer, confirming that the information contained in the property sets is correctly reflected in the model.

Figure 4 shows the graphical result of the modeling, including terrain, alignment, and extruded solids representing the layered road structure and the modular paving.

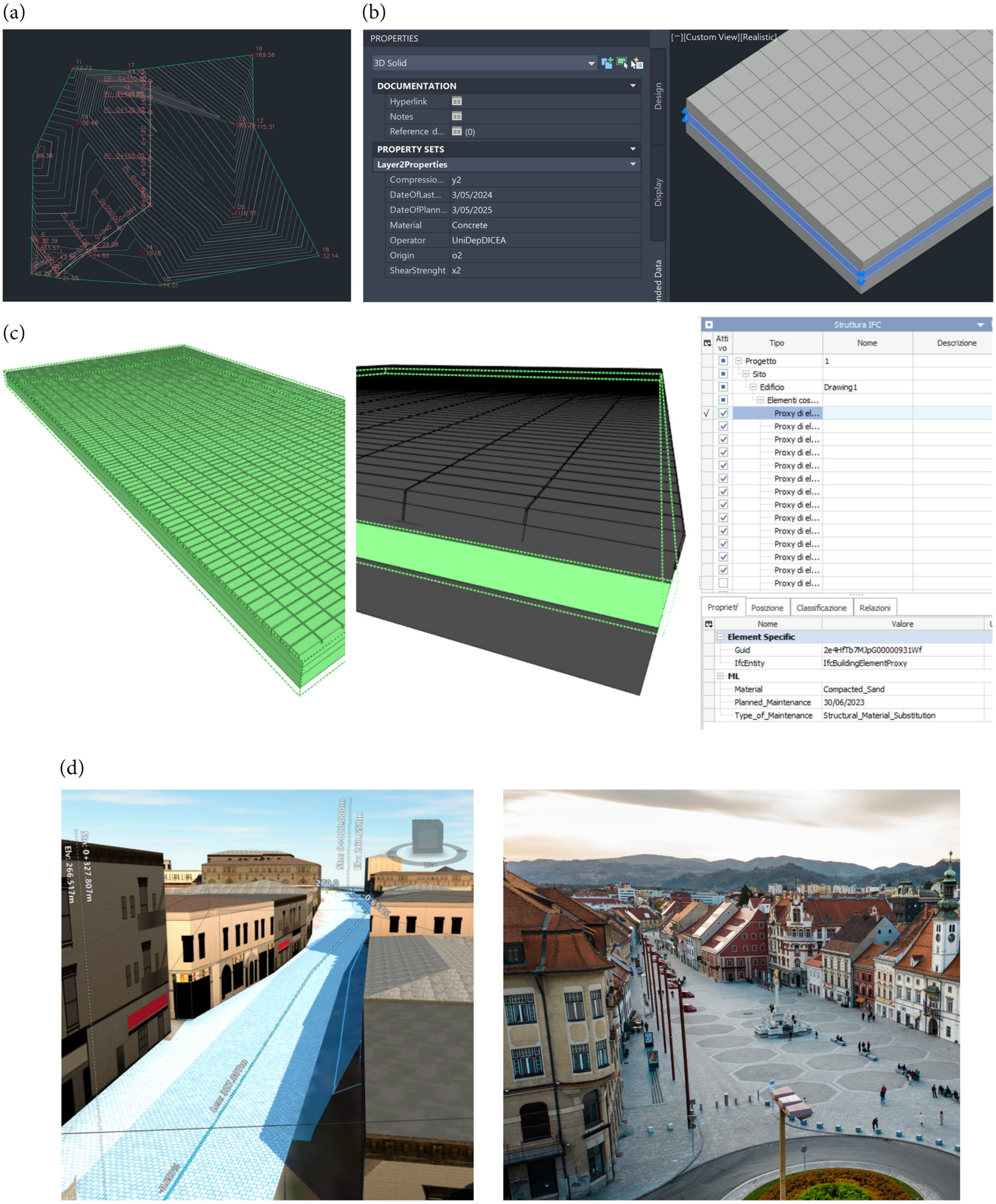
As for the real-case scenario, the visual script implemented in Dynamo was applied without modifications. Despite the presence of staggered rows in the actual stone layout, the current version of the algorithm only supports regular patterns of flagstones. This limitation, however, did not significantly compromise the effectiveness of the simulation, which remained suitable for asset management analysis.

Due to restrictions on accessing municipal datasets, the maintenance data used in the application were simulated. Nevertheless, they were constructed to reflect realistic values, including properties such as the last intervention date, planned maintenance date, operator designation, and mechanical performance attributes of the paving materials (e.g., compressive and tensile strength).

The real-case application demonstrates the robustness and flexibility of the proposed workflow. Even in the presence of

Figure 4

Graphical result: (a) topography and alignment in Civil 3D main interface; (b) corridor, road solids and Property Sets, in Civil 3D main interface; (c) road solid works and Properties Sets in Open IFC Viewer; and (d) real-case scenario results



irregularities typical of historical urban settings, the use of structured data and procedural automation enabled the generation of a semantically rich BIM model that can be used for visualization, communication with stakeholders, and future integration into asset management systems. The limitations identified, such as the lack of staggered pattern recognition, will serve as the basis for future development of enhanced geometry-handling capabilities within the algorithm.

The IFC-SPRO ontology structure is shown in Figure 5.

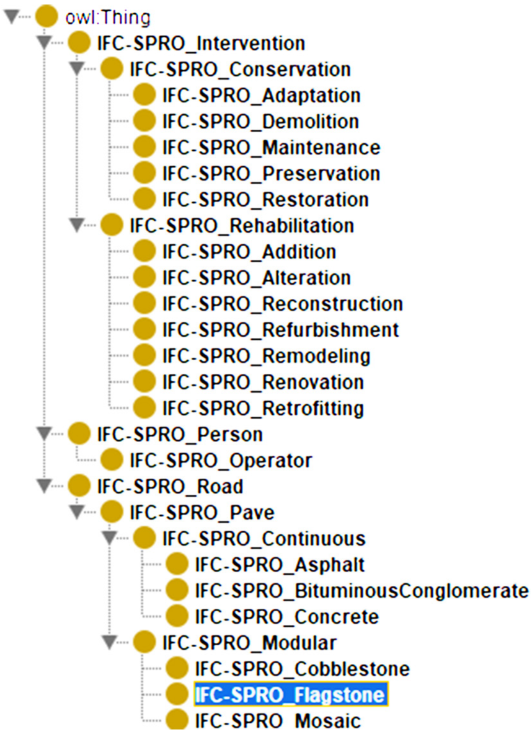
Three main classes are represented: Interventions, Person, and Road. The first has two main subclasses, Rehabilitation and Conservation,

Table 1
KPIs for methodologies comparison

Metric	Baseline (Manual)	Proposed (Automated)
Modeling time	3–6 hours	Less than 30 seconds*
Operator dependency	High	Low
Risk of input error	Medium-high	Low (data-driven)

*Excluding data preparation time.

Figure 5
IFC-SPRO ontology modification schema of IFC



whose definition accords with the ICOMOS [55]. The Person class has only one subclass, the Operator. The Road class has one subclass as well, for the pavement representation, Pave. Pave has two subclasses, for Modular pavements and Continuous pavements, which have three subclasses each. Here lies the IFC-SPRO_Flagstone subclass, where the instances of each flagstone modeled previously in the ifc/ttl file are imported. In Figure 4, it is shown that it is possible to observe that the flagstones are represented in the IfcBuildingElementProxy class, while the IFC-SPRO_Flagstone contains all the instances inherited from the original IfcBuildingElementProxy class.

After defining the classes and sub-classes making up the ontology structure, it is fundamental to assign Object Properties to the objects of the ontology (i.e., instances, or individuals, via their classes). For example, the property IsResponsibleOf was created, having the Intervention class as domain, and thus all the individuals of that class, and the Road class as range, thereby all the individuals of that class.

Next, the Data Properties were assigned, as First Name and Last Name, for the class Person, and Street Name, for the class Road. Being Operator a subclass of Person, it inherited Person's properties. Therefore, any individual pertaining Operator class has First Name and Last Name data properties. The same happens for the individuals pertaining to any subclass of Road: they will have the Street Name data property.

Based on the IFC-SPRO_Flagstone ontology, the instance ontology was used to create a knowledge graph using a SPARQL query (Figures 6 and 7).

Further, we extracted the knowledge about the operator responsible for maintenance operations with the following SPARQL query:

```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX spro: <https://ifc-spro.owl/>
PREFIX ifc-spro: <https://ifc-spro.owl#>

SELECT ?maintenance ?lastMaintenance ?firstName ?lastName ?streetName
WHERE {
 ?maintenance rdf:type spro:IFC-SPRO_Maintenance .
 ?maintenance ifc-spro:last_maintenance ?lastMaintenance .
 ?maintenance ifc-spro:IsResponsibleOf ?operator

 ?operator ifc-spro:first_name ?firstName .
 ?operator ifc-spro:last_name ?lastName .
 ?maintenance ifc-spro:IsMaintained ?flagstone .
 ?flagstone ifc-spro:street_name ?streetName .
```

Data returned from the instance ontology by means of the SPARQL query allow to ascertain whether the maintenance has taken place or not, the date of the last maintenance operation undertaken, first and last name of the operator responsible of the maintenance, and the street name.

6. Conclusions

Through the provision of a thorough workflow, a method for modeling in BIM was proposed with this study endeavor. The innovative aspects that were investigated are as follows: (i) the development of a reusable, fully automatic modeling tool that reduces the modeling time from hours to seconds (excluding data preparation); (ii) the focus on road paving with stone elements; and (iii) the innovative approach to geometric and semantic modeling, fully realized in a visual programming environment.

In addition to the experiences from the literature cited above, where attempts to exploit the potential of VPL were limited to integration with the main software, a workflow is proposed to allow non-expert users to obtain road models from a set of input data, which can be a great advantage for companies and AECO specialists who can save time and money on staff training.

Compared to existing literature, the proposed methodology demonstrates superior computational efficiency and automation. Unlike Python-based routines [35] or semi-automated Scan-to-BIM approaches [34], our VPL-based workflow generates a fully parametric and semantically enriched model in a very short time on standard hardware. Traditional methods for stone pavement modeling, such as Biancardo et al. [36], rely on manual processes and advanced surveying, making them time-intensive and less scalable. Additionally, while semantic ontologies have been explored for transport systems [42], accident modeling [44], and risk assessment [45], this study introduces the first domain-specific ontology (IFC-SPRO) tailored for modular stone pavements within a BIM context. In contrast to Jha [23] and Zhang [30], who focus respectively, on parametric layout and ML-driven

Figure 6
SPARQL query for knowledge graph creation based on the instance ontology

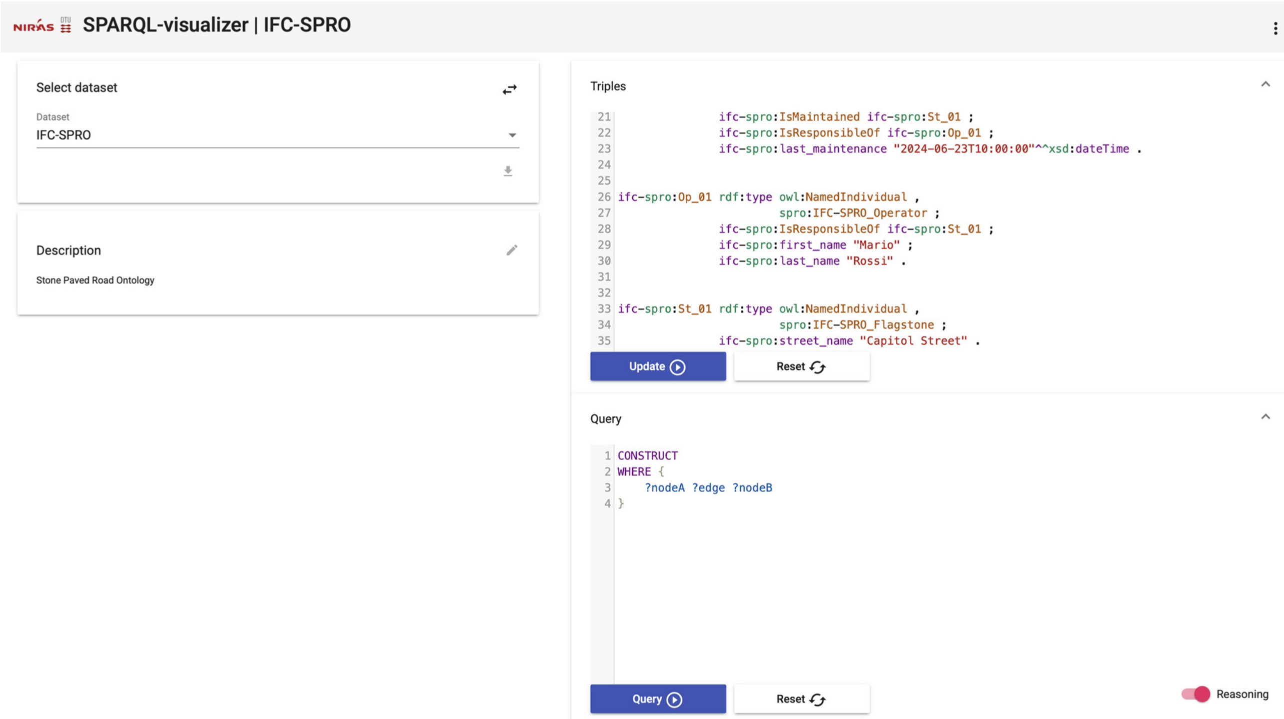
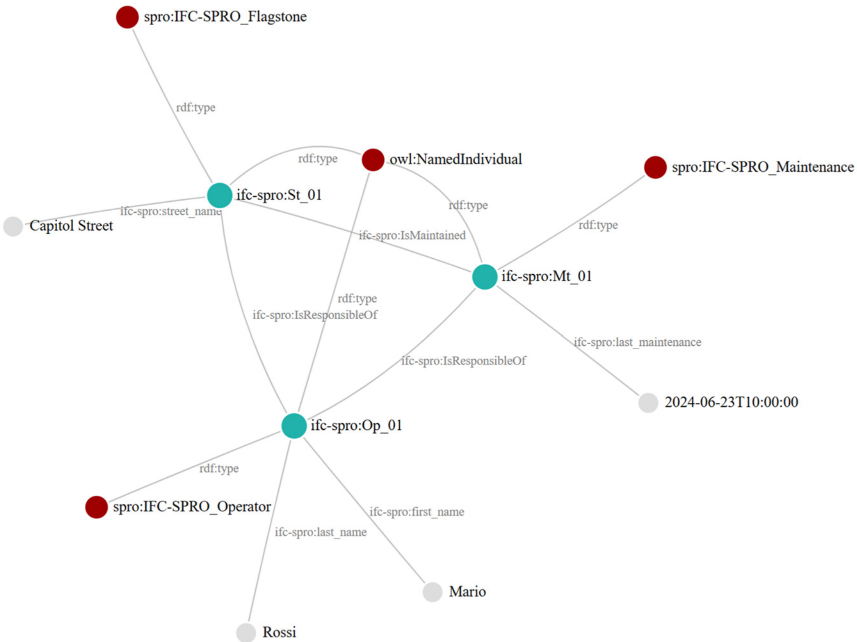


Figure 7
Knowledge graph of the instance ontology



deterioration forecasting—both with higher setup or computational costs—our solution integrates geometry and knowledge representation efficiently. This addresses the gap noted by Collao et al. [32] on the limited use of VPL in infrastructure BIM, offering a reusable, accessible, and semantically powerful modeling tool.

Regarding semantic modeling, with respect to the state of the art on ontologies, the semantic web, and the IFC standard for interoperability in the BIM environment, the present work contributes to the expansion of the standard through the modification of the standard to cover the classes related to the modular elements of stone paved roads. The IFC-SPRO is the first ontology developed for applications to stone-paved roads.

While the IFC 4.3 standard offers significant improvements for the semantic modeling of linear infrastructures, covering roads, railways, tunnels, viaducts, and ports, it could not be adopted in this study due to technical constraints. Specifically, the export functionality of Autodesk Civil 3D does not natively support IFC 4.3: an external extension is required, and this often entails a custom object mapping process that remains unstable or partially documented.

Furthermore, the current IFC-to-OWL conversion tools, including those based on the EXPRESS schema, are not yet fully compatible with IFC 4.3.

However, IFC 2x3 presents significant semantic limitations: the exported model cannot distinguish between infrastructure-specific elements, and all road components—including the modular pavement—are mapped to generic IfcBuildingElementProxy entities. This limitation affects not only the semantic granularity of the resulting RDF graph but also the potential for machine reasoning and domain-specific inference.

Despite these limitations, we demonstrated that our workflow still supports meaningful semantic enrichment through the custom IFC-SPRO ontology, which bridges the semantic gap by defining road-specific concepts externally. This approach makes it possible to perform SPARQL-based queries and reasoning over infrastructure models even when starting from IFC 2x3—thus providing a functional workaround until full IFC 4.3 support becomes technically viable within the toolchain used.

The use of spreadsheets for source data definition, ontologies, and SPARQL for semantic enhancement allowed for the creation of a powerful modeling tool based on an algorithm created in a visual programming language environment for geometric and semantic modeling.

The main benefits are getting a high-quality road BIM model quickly, reducing the need for extensive training.

Companies may significantly improve their operations when this strategy is adopted, and algorithms are created to adapt to regulatory criteria, for instance, related to the Level of Information Needed (LOIN). It can be used as a starting point for more in-depth modeling based on their own unique needs.

However, it is important to highlight some of this study's limitations.

The technique is reusable; however, it only applies to a specific spreadsheet template (Section 3.3). Making the study more adaptable, possibly using AI and neural networks so that it can comprehend whatever spreadsheet template the business would need to create would be a positive advance.

The algorithm operates with a specific deployment pattern for flagstones. It thus also has geometrical limitations. As a result, from this perspective, it would be ideal to build the algorithm to be able to model any sort of patterns, covering the most prevalent and often utilized patterns in historical city centers.

Despite these drawbacks, this work will serve as a springboard for further research in this field, where several algorithms can be created, utilizing VPL to better automate the modeling processes in BIM, whether for the planning, design, construction or maintenance phases. To cover all aspects of the BIM methodology, the research can be expanded to include pre-dimensioning, structural analysis, implementation of economic, technical, environmental sustainability assessments, or construction scheduling.

Funding Support

The research was developed within the Project of National Interest - PRIN 2017 "Stone Pavements. History, Conservation, Valorisation and Design" (20174JW7ZL) financed by the Ministry of Education, University and Research (MIUR) of the Italian Government.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Mattia Intignano: Conceptualization, Methodology, Software, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Visualization. **Salvatore Antonio Biancardo:** Conceptualization, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Sara Guerra de Oliveira:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization. **Andrej Tibaut:** Conceptualization, Methodology, Software, Resources, Data curation, Writing – review & editing, Supervision. **Gianluca Dell'Acqua:** Conceptualization, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration.

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How to Cite: Intignano, M., Biancardo, S. A., Guerra de Oliveira, S., Tibaut, A., & Dell'Acqua, G. (2025). Semantic-Driven Automation of BIM for Stone-Paved Roads: An Ontology-VPL Integrated Approach. *Journal of Computational and Cognitive Engineering*. https://doi.org/10.47852/bonviewJCCE52025931