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BIM Approach for Smart Infrastructure Design and Maintenance Operations

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Abstract

In the age of the Internet-of-Things and Big Data, Building Information Modeling (BIM) is being expanded into sectors for which it was not originally designed, such as the infrastructure sector, and becomes a necessity for the planning and management of smart cities. The digitization of the urban environment, its building and infrastructural heritage and its services is at the center of the concept of smart city, and this appears strongly linked to the use of BIM on an increasingly extended scale as an enabling tool for planning cities that are increasingly intelligent, sustainable, interconnected and above all liveable. In this chapter a creation process for the digitalization of existing roads, as well-known as reverse engineering method, will be shown as follows: a) modeling 3D digital terrain model; b) creating the horizontal alignment, vertical profiles and editing cross-sections; c) modeling the 3D corridor. As a response to long-term development between BIM and road engineering, this chapter will contribute also by offering innovative and practical solutions for integration of road design and pavement analysis, for a better management and optimization of road pavement maintenance.

Keywords: building information modeling, smart infrastructure, road pavements, computational design

1. Introduction

Smart city is to lead the transformation of urban development with innovation, comprehensively promote the new generation of information and communication technology and the new urbanization development strategy, deeply integrate and improve the modernization level of urban governance capability [1].

A self-respecting smart city cannot ignore serious and far-sighted planning that bases urban landscape design on Geographic Information Systems (GIS) and integrated modeling, which Building Information Modeling (BIM) is able to ensure; this is because only having a clear vision, implemented with a precise planning, of what is going to be built is it possible to avoid the destructive effects that a construction practice without adequate tools can cause. The use of GIS and BIM together therefore allows you to plan, design, build and manage infrastructure resources more efficiently and save time and money.

BIM is widely recognized as a fundamental methodology for relaunching the global economy: this is why in many countries digitalization processes have been started in the AEC sector [2].

BIM starts at the planning and conceptual design stage and continues throughout the lifecycle of the asset. It is important that intelligent information is not lost as the project progresses through the various stages of a BIM Infrastructure Project.

The entire process of developing, executing and managing infrastructure projects can be transformed—initial surveying and data collection, environmental review, public participation, design and documentation, bidding, construction, and operations and maintenance [3, 4]. The model-centric approach enables planners, engineers, and designers to explore and validate innovative design ideas and what-if scenarios with project investors.

To model a smart infrastructure, it is necessary to find a set of variables and parameters essential for the analysis and prediction of the performance of built objects [5].

Data modeling can be performed by procedural, also known as parametric, modeling that provides object-oriented n-dimensional information or generative model information containing objects created through algorithmic processes [6].

Parametric and procedural 3D geometrical models can be represented by graphs in order to define relationships and dependencies between geometric entities and allow its reuse in similar design scenarios or to adapt it to different scenarios [7, 8].

The models created for BIM are not just 3D geometry; they are data-rich objects which are: intelligent - parametric engines help define relationships between objects and keep changes consistent and coordinated; knowledge-based - can be constrained by things like AASHTO codes, design criteria, and company standards; scalable - able to aggregate huge amounts of data from multiple sources; visual - enable better analysis, simulation and communication [9].

In the last few years, researchers have been focusing their attention on assessing the benefits of using digital tools and processes to support effectively the entire life of transportation facilities and road infrastructures, from strategic planning, design and construction [10–17] to performance management and maintenance [18–21].

Marzouk and Othman [22] proposes an inclusive framework for integrating Building Information Modeling (BIM) and Geographical Information System (GIS) to plan and forecast the utility infrastructure needs for expanding and emerging cities to highlight the concept of “smartness” during the planning stage.

As highlighted by Sankaran et al. [23], BIM is an efficient method for collecting and updating as-built data for creating a digital archive of information to facilitate management and future project development.

For example, Tang et al. [24] created a platform for the integration of Building Information Modeling (BIM) based road design and pavement structural analysis, allowing to establish a conversion between the three dimensional (3D) model and the finite element method software ABAQUS, providing quality data and powerful technical support and minimizing the uncertainty factors in the road design and maintenance processes.

Also, the design process was supported through the implementation of an empirical model for the analysis of permanent deformation of the asphalt pavement, which allows selecting the pavement that best suits the desired service life [25].

There is a need for such an approach to assist decision makers to ensure enterprise's objectives and targets are maximized with given budget and planned shutdown time [26, 27].

Interoperable BIM model has been adapted to perform complex multi-physical studies and simulations in several technical fields (including noise exposure,

wind comfort, artificial and natural lighting, energy consumption, environmental impacts and global comfort) [28].

However, the existing BIM-based decision-support methods have primarily focused on building design and construction. Therefore, they are limited in their ability to provide an appropriate methodology for master planning of large-scale development projects [29].

It is of great significance to promote the application of BIM technology in the life cycle management of projects in the context of smart cities, ensure the consistency and interoperability of BIM deliverables at all engineering stages, and realize the comprehensive management of the construction industry in smart cities [30, 31].

2. Goals definition

Analysis procedure presented here aims to offer an innovative and practical methodology for integration of road design and pavement analysis, for a better management and optimization of road pavement maintenance.

The work phases are shown in **Figure 1** and basically are carried out as follows:

1. Building the existing ground surfaces; surfaces are used to derive alignments and profiles, and for corridor grading;
2. Designing horizontal-vertical alignment; alignment are used by corridor as its centerline while profiles use existing ground profiles and design finished grade profile (vertical alignments);
3. Create the required assemblies; subassemblies are used to build the required assemblies;
4. Create the 3D corridor;
5. Information management for a decision support system for the management of maintenance processes.

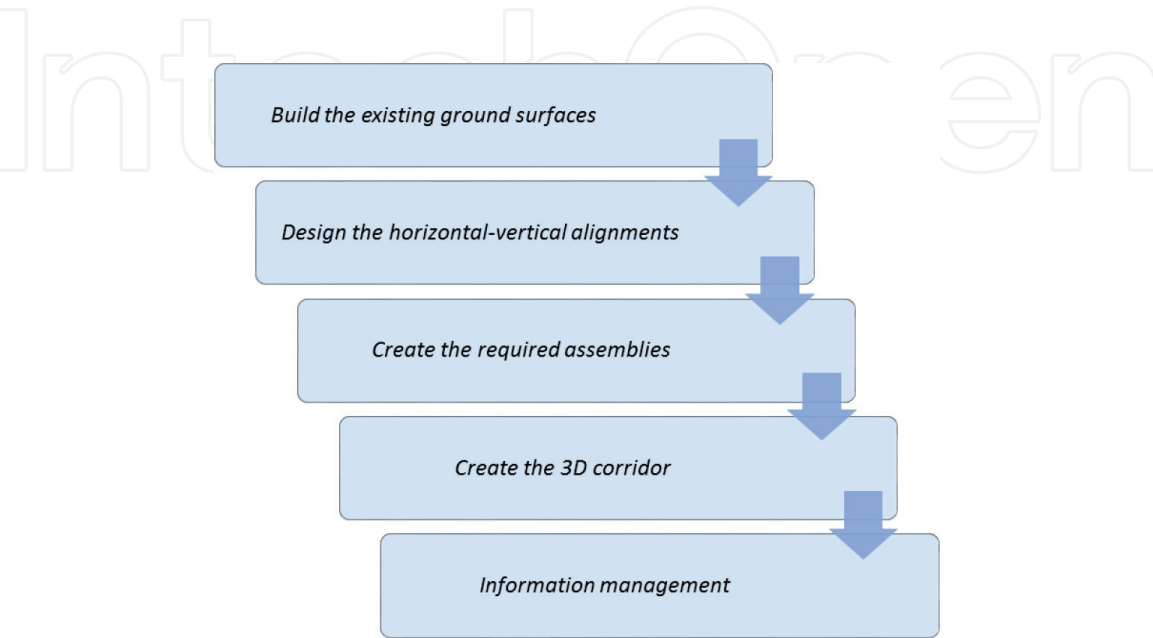


Figure 1.
Methodological approach.

3. Road modeling

3.1 Digital terrain model

Digital Terrain Modeling (DTM) is a concept that underlies all calculations in Civil Engineering involving elevation or slope - profiles, cross sections, grading and volume calculations.

The process of DTM involves the creation of a data structure that the software can instantly “touch” to retrieve elevations or slopes, representing either existing or proposed conditions.

DTM mathematically completes all interpolation possible between the data supplied, and stores the result in a digital file for easy retrieval.

Surfaces can certainly be produced from other data types, including point data.

There are certain data types that are universally applicable to any DTM effort in Civil Engineering and Surveying. These data types are constant in any program: Civil 3D, Open Roads Designer, ArcGIS, etc.

The three data types which can be used in constructing a DTM are Point Data, Breakline Data, and Contour Data.

- **Point Data** - Point Data for DTM consist of individual discrete X, Y and Z locations, without connecting features between them. Typically, these will be spot elevations in a contour drawing, or the mass points themselves in a Mass Points and Breaklines drawing. Critically, the Point Data must have an elevation or Z component that can be processed in some fashion in building the elevation model. Spot elevation text at elevation 0 in a drawing can be used and processed by Map into an ASCII file, and ASCII files of XYZ format can be used as well.
- **Breakline Data** - Breaklines are also referred to as Faults, or Features. Breaklines, as used in this context, represent the linear edges of site features along which there is a noticeable change in grade. Successfully applied, a breakline forces a deflection in a contour to show a grade change. Examples are edges of pavement, shoulders, toes or tops of slope, toes or tops of wall, water features, etc. λ **Contour Data** - The definition of contour Data for Digital Terrain Modeling is very specific, and not necessarily what one would expect.
- **Contour Data** are strings of point data connected by segments in complex objects; the CAD representation is a polyline. Contour Data do not have to be at constant elevation, as one typically thinks of contours. Contour Data are a fast means of selecting and processing point data, utilizing the vertices of the objects. Most Digital Terrain Modeling applications will also process the segments between the vertices as breakline data, and can filter out vertices too close together or add interpolated vertices if required. Contour Data must be at a correct Z elevation to be processed in a Terrain Model. Polylines must be at a correct Z, either constant as a 2D polyline, or varying, as a 3D polyline. GIS data can again be used, and CAD Map can read elevation attributes from GIS Contour Data and apply them to polylines through a Property Alteration Query.

Most Civil Engineering and Surveying applications will utilize some combination of data types in a Terrain Model; having two types present is common and all three is not unusual at all.

Triangular irregular networks (TIN) are a representation of a continuous surface consisting entirely of triangular facets, used mainly as Discrete Global Grid in primary elevation modeling.

TINs can be constructed using three types of vector information: altitude measurements (mass points), surface continuity breaklines, surface continuity break polygons (polygon surfaces).

The points contain the X, Y coordinates and the Z value. All points are used to establish a connection with the two closest points to create triangles. Surface triangulation is based on the Delaunay algorithm, which ensures that no points are within the circle of a triangle.

The Discontinuity Lines represent the characteristics of a linear infrastructure such as curbs, retaining walls, etc. These lines also define the edges of the triangles. Breaklines can be created from linear entities such as line, polyline, arc, circle.

Contours are the characteristics to define bounded 3D surfaces. Surface contours can be created with closed polylines. Defining external contours on a large 3D surface improves the performance of a TIN Surface plane.

Figure 2 shows the triangles that result from Digital Terrain Modeling where the elevation value is retrieved from the digital surface and displays it in the Tooltip, instantly, and anywhere on the surface.

3.2 Horizontal-vertical alignment

Creating and defining a horizontal alignment is one of the first steps in infrastructure design.

In **Figure 3** a workflow to design and edit alignments is shown.

You can draw the alignment geometry as a polyline, and then create the named alignment from that geometry. For greater control, you can create an alignment object or You can also make edits to alignments using grips.

Create alignments in many ways, such as creating them from polylines, from pipe networks, and from LandXML data.

The alignment can be created using fixed, floating, and free elements:

- Fixed elements have its position totally defined by specifying a combination of start/end points or center, length, bearing or angle, and radius. However, as the fixed position of a computer is defined by points that are dependent (referenced) on other elements, a fixed computer is actually free to move as the referenced elements move. It is “fixed” in respect of its location to the referenced element;



Figure 2.
Digital terrain model.

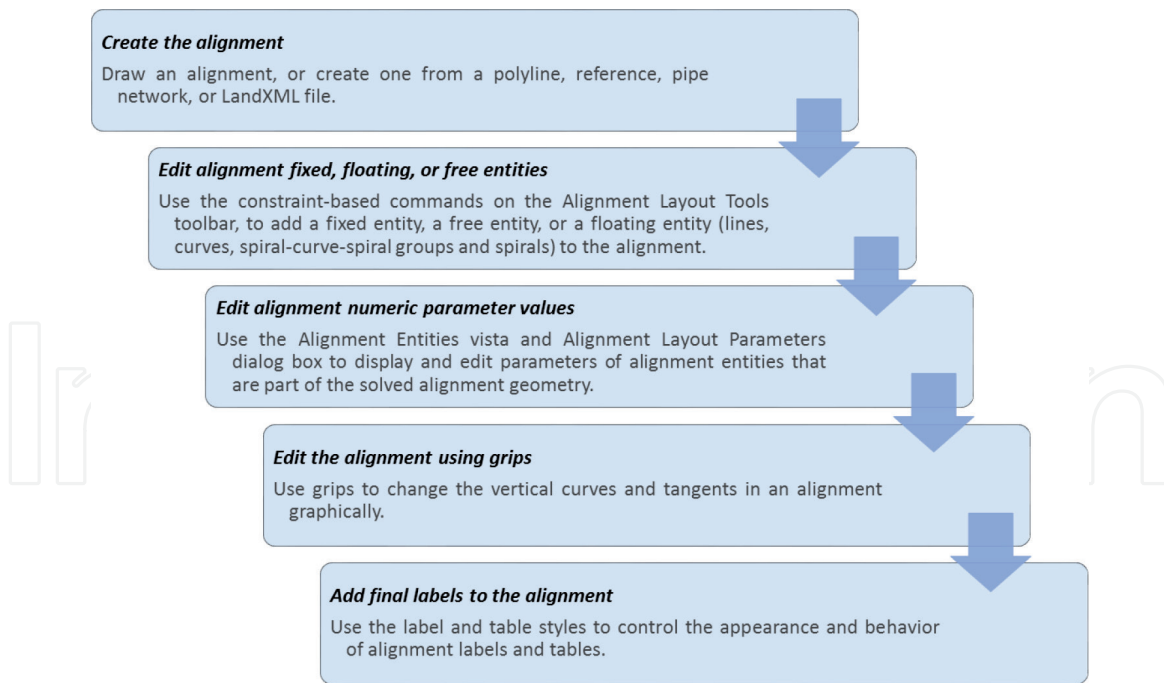


Figure 3.
Workflow: To design and edit alignments.

- Floating elements have one unknown, which becomes the “floating” part. The unknown part can be the length, angle, point/centre, or radius. The other parts (one for lines, two for arcs) are fixed in position;
- Free elements are totally unconstrained and will be defined by the adjoining elements. Whilst an arc has two unknowns with only the radius, or one point, or length defined.

Once it is determined which element type best suits the design context, it can be selected the appropriate line, curve, transition, or combination based on available design data, such as whether you have a known through point, length, or radius.

When you create an alignment, you can use the criteria-based design feature to ensure that your alignment design meets minimum local standards and consequently easily identify and report standards violations.

The alignment is an interactive line with profiles, both existing ground and planned work.

Using profiles, you can view changes in elevation along a horizontal alignment. In addition to the centerline profile, you can create offset profiles for features such as waterway or ditch banks. On a profile view, you can also superimpose the profile of a different horizontal alignment that is in the same area. And like LandDesktop you can create a temporary profile that can help you view information at locations where there is no alignment (i.e. line, polyline, feature, or along a series of points you select).

The horizontal and the vertical alignments need to match in length exactly or else the corridor will not be created properly.

Figure 4 shows an example of road alignment with its relative ground and vertical profile.

Once both alignments are created, the next step is to create a section type, with surface depths, sub-earth depth, kerbing, banking, etc.

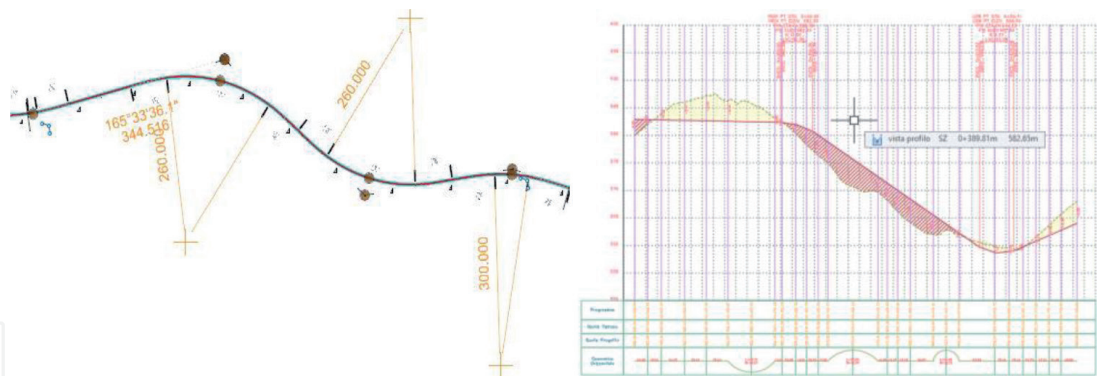


Figure 4.
Road alignment and its vertical profile.

3.3 Section type

Assembly objects contain and manage a collection of subassemblies that are used to form the basic structure of a 3D corridor model.

An assembly is an 3D drawing object that manages a collection of subassembly objects. Together, assemblies and subassemblies function as the basic building blocks of a roadway or other alignment-based design.

Adding one or more subassembly objects, such as travel lanes, curbs, and side slopes, to an assembly baseline creates an assembly object. This forms the design for a corridor section. The subassemblies are provided in a set of catalogs.

It is also possible to create more advanced assemblies referred to as conditional assemblies. A conditional assembly contains one or more conditional subassemblies, which apply subsequent subassemblies when specified conditions at a given station are met.

In **Figure 5** is shown a typical section type for fill and in presence of a bridge.

Specific BIM-based tools as Subassembly Composer/ Generative Components provide an interface for composing and modifying complex subassemblies, without the need for programming. Without the need to be an expert in programming, users can create custom subassemblies to meet their specific needs, making corridors have endless possibilities.

For example, in presence of a retaining wall characterized by a variation of the geometric characteristics in terms of height/weight along the road layout, it is possible to create a flowchart (see **Figure 6**) set with decision variables that change as the boundary conditions vary.

In the case in question, the section changes dimensional characteristics as the distance between the road surface and the ground surface changes.

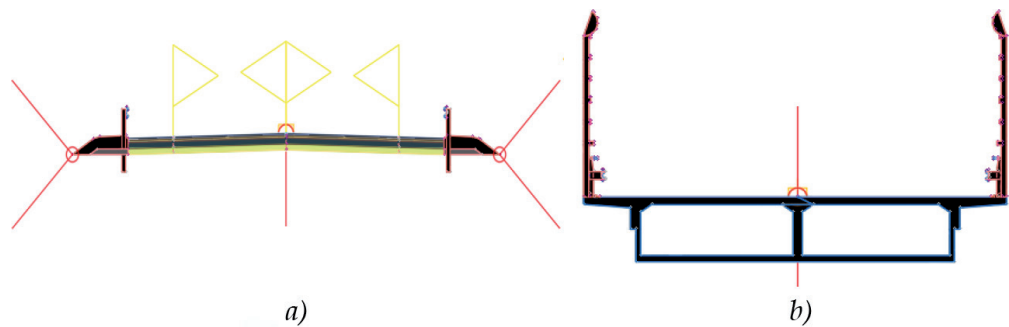


Figure 5.
Section types. (a) Fill, (b) bridge.

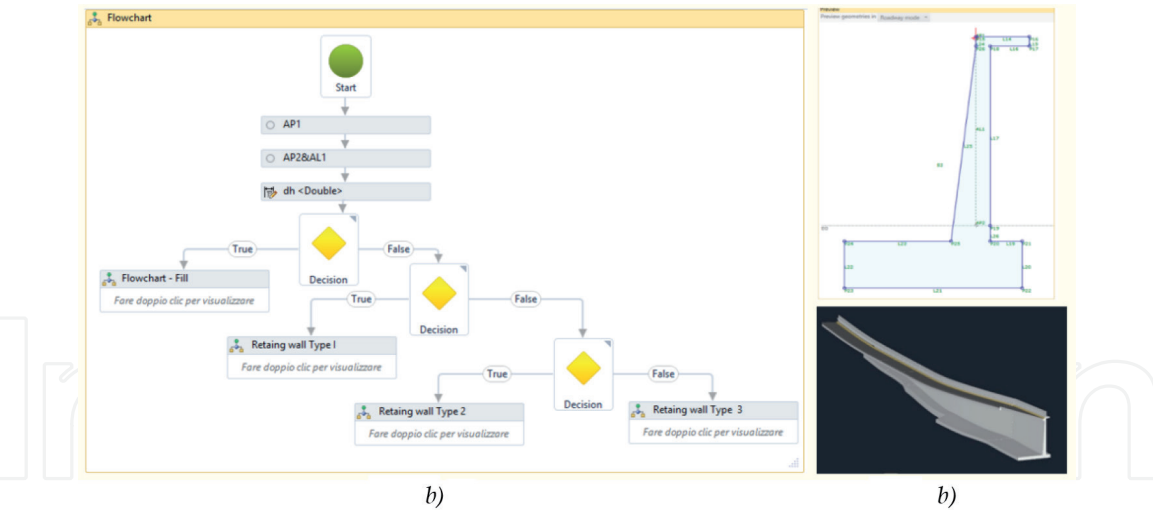


Figure 6.
Modeling retaining walls using subassembly composer. (a) Workflow, (b) result.

Once your assembly is built you need to apply this to your alignment using the corridor function and hey presto, you will have a corridor and basic road design.

3.4 Corridor modeling

Before create corridors, you must have existing data, such as existing ground surfaces, alignments (centerlines), profiles (vertical alignments), and typical sections (assemblies).

All calculations should be finalized before they are applied to the corridor model. Changes in a corridor baseline alignment are not reflected in calculations. Changing the design criteria does not update the corridor model.

In **Figure 7** is shown a generic 3D Corridor model.

3.5 Information management

Once a road network is correctly modeled and parameterized following the above procedure, a number of shared parameters describing the main features of pavement materials can be created to match the information contained in an external database.

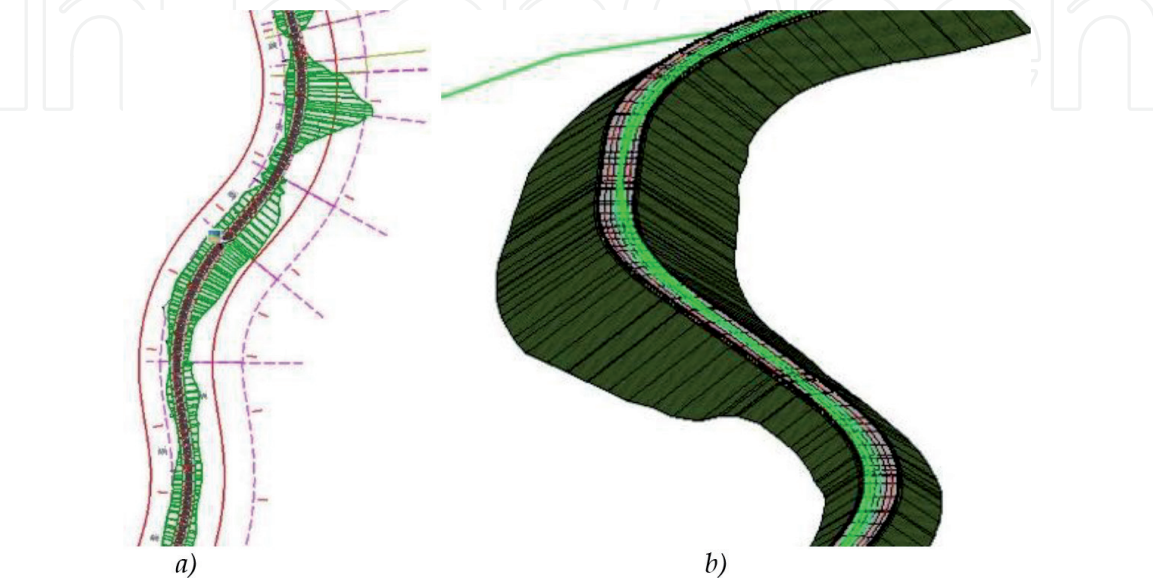


Figure 7.
Modeling corridor. (a) Plan view, (b) 3D view.

There are several visual programming tools (VPL) (i.e. Dynamo) that give to users the possibility to visually script and define custom pieces of logic using various textual programming languages.

The shared parameters imported in the current project as materials features, were the road name, the road administration authority, the year in which the material was layed in place during routine maintenance operations and the physical and mechanical features of the wearing course mixtures, namely bitumen content, air voids percentage calculated with bulk specific gravity determined by means of the dimensional procedure, SSD procedure or sealed specimen procedure and Marshall stability.

Then, the material codes were exported to Excel with the programming flow reported in **Figure 8**, then matched with the materials names in the worksheet and finally imported back into VPL with assigned values.

A worksheet was created using the code block “Data.ExportExcel” (5), whose file path, sheet name and position of the exported data were defined respectively with the code blocks (4A), (4B) and (4C). The worksheet contained a list (4D) of materials identifiers (3A) and names (3B) selected from the list of elements (2) of the materials category (1).

The above mentioned operations allowed visualizing and managing the physical and mechanical features of the wearing course model and updating the information once the input worksheet is integrated with different data. The visualization of the imported data is visible in the material parameters interface, as shown in **Figure 9**.

Then, in the same way, is possible the implementation of a ranking algorithm to evaluate the durability of the wearing course material basing on the material characterization, according to current Regulation [32]. In the specific:

- % bitumen (%B) in the range 4.5 ÷ 6.1% to meet both economic and environmental needs;
- Stability>900 (daN) to respond to mechanical problems;
- % air voids determined by means of the dimensional procedure >3% to improve shear strength;
- The difference between air voids determined by means of the sealed specimen and SSD procedure (Δ) is equal or lower than 1% to ensure that there are no anomalies in the database due to technical errors.

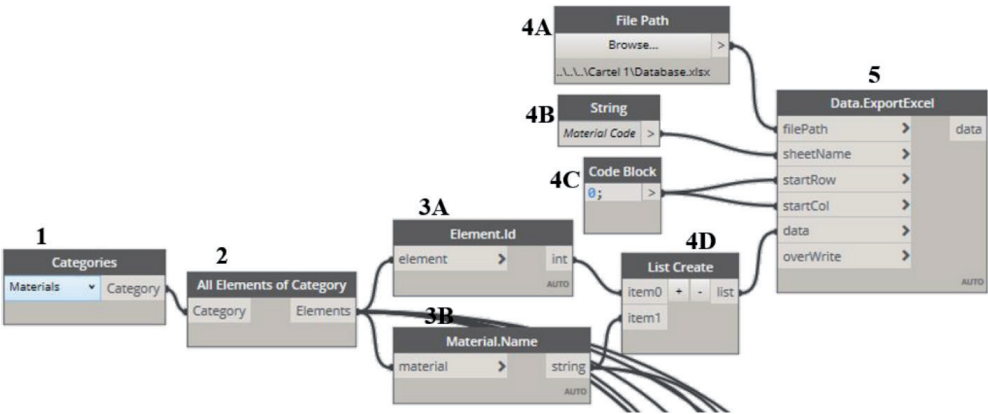


Figure 8.
Materials code creation workflow.

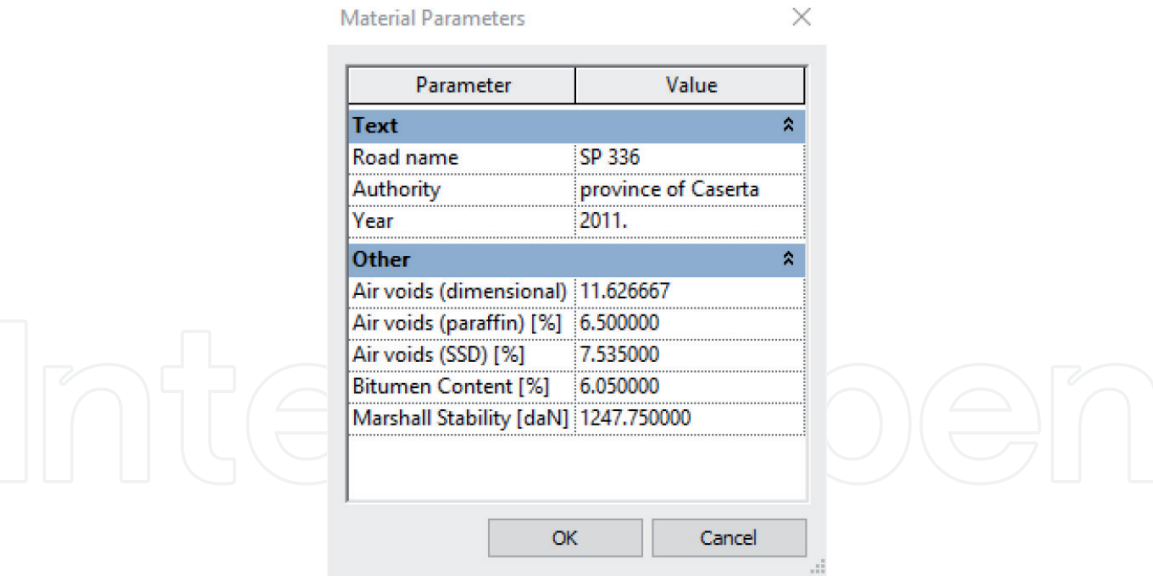


Figure 9.
Example of material parameters after the association of worksheet data to the model.

In **Figure 10** is shown the workflow for identifying the road pavements that satisfy the first condition.

In the specific: box 1A answers the question if x (%B) is greater than or equal to y (%B lower-limit equal to 4.5%); box 1B answers the question if x (%B) is less than or equal to y (%B upper limit equal to 6.1%); Box 2 “List.Join” concatenates the two lists into one list; Box 3 “List.AllTrue” determines if all the elements of the list are Boolean values with true value; Box 4 “List.Join” merges all the lists associated to other pavement sections of the road network; box 5 “SelectModelElement” for selecting the pavement sections under analysis; box 6 “List.Create” for merging all the selected pavements in the previous step in a single list; box 7 “List.FilterByBoolMask” to filter the list of elements codes by looking up for corresponding indices in the list of Boolean variables, identifying the sections that comply with the technical specifications.

In the same way, the workflow can be adapted to the remaining Regulation conditions, with the possibility then to create combined filters among the mentioned

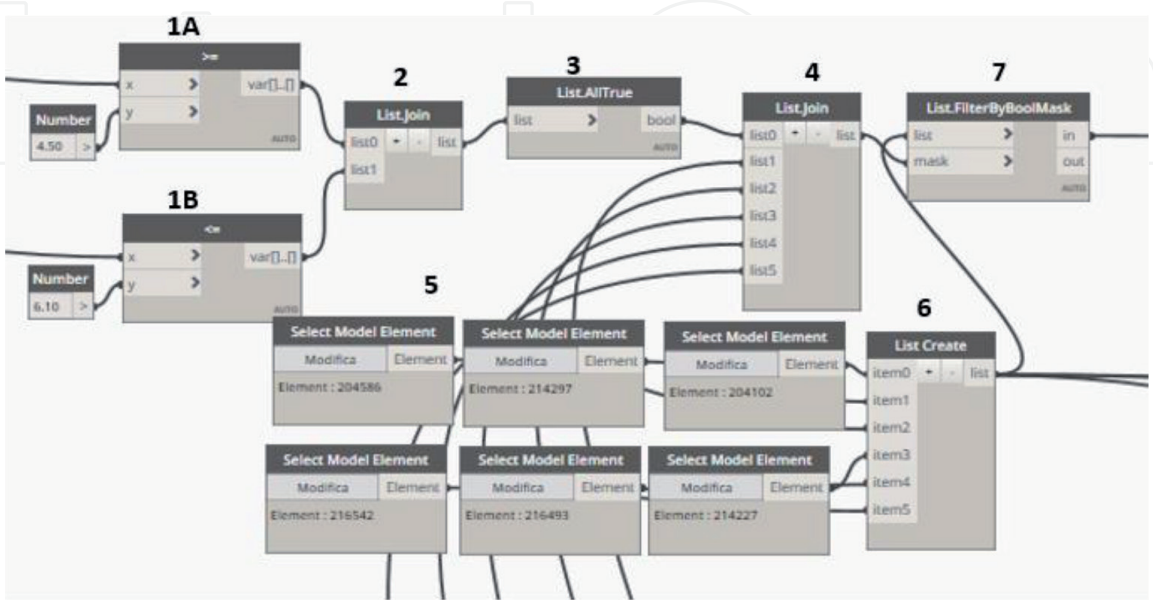


Figure 10.
Workflow for identifying pavements with bitumen content in the range 4.5%–6.1% by the weight of the mixture.

conditions, for visualizing on the road network map, with different color, the pavements with best, worst or intermediate performance.

For example, in **Figure 11**, the list containing the overall scores of the road surfaces under analysis (1) was matched with the list of identification codes of the corresponding elements of the model (3) using again the code block “*List.FilterByBoolMask*” (4). In the present study, the list of Boolean variables was obtained by looking for the road surface with the minimum score (2), obtained from the combination of several physical and mechanical indicators and their upper and lower limit imposed by the Regulation. Lastly, the element code that met condition (2) was emphasized in the model element with the color red (5) by using the code block “*Element.OverrideColorInView*” (6).

As a simplified application to show the impact of information update on the model output modification, two different road sections were considered with bituminous mixtures for wearing course characterized in terms of bitumen content, percentage air voids and Marshall stability.

The test results are updated as material parameters in the model and a ranking algorithm is implemented in order to identify the road section with a need for maintenance. As shown in **Figure 12**, the critical road section that requires routine maintenance before the other is highlighted in red.

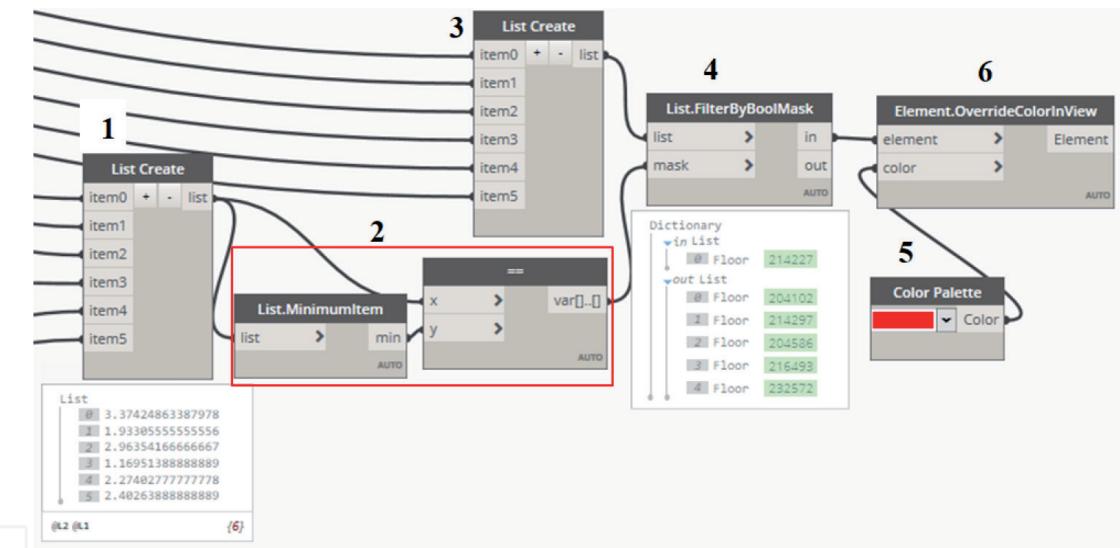


Figure 11.
Workflow for identifying pavements with best/worst performance on the road network.



Figure 12.
Example of identification of the critical section.

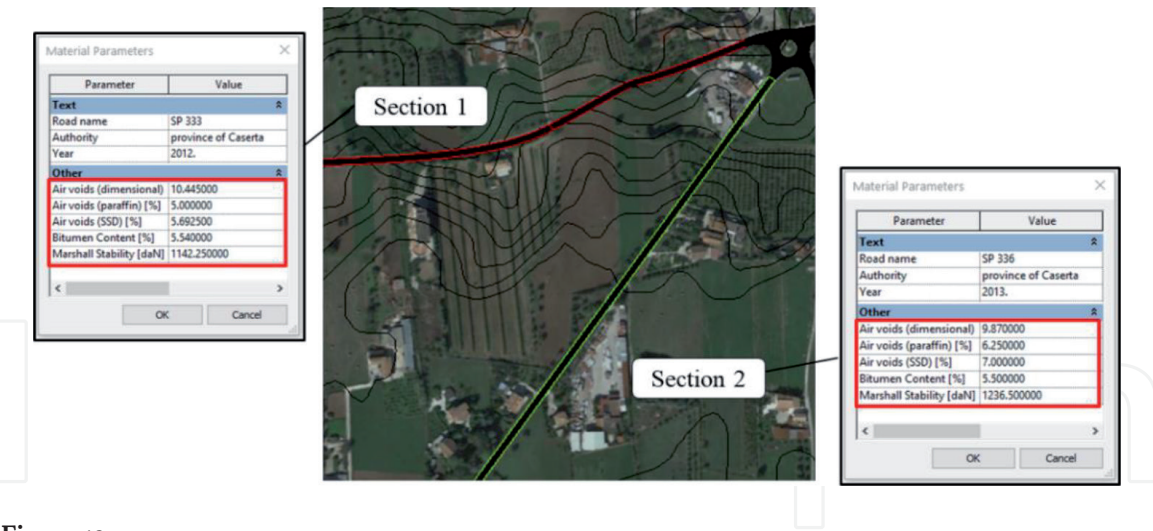


Figure 13.
Example of identification of the critical section after routine maintenance operations.

After routine maintenance operations, quality controls are performed on the wearing course to assess the compliance of the material with the performance required by the Regulation. As a consequence, the model is updated with new information and the raking algorithm immediately finds out the new critical section (**Figure 13**).

4. Conclusions

Computer-aided drafting (CAD) transformed the way professionals created infrastructure designs.

If oriented to the management phase, a BIM model becomes a real simulation, planning and implementation tool for the facility manager, also thanks to the three-dimensional approach related to the parametric objects that populate the environment, representing a valid tool to guarantee control and interoperability of data in an intelligent way.

The implemented methodology allowed creating an integrated model that contains and analyzes data produced by the quality controls of the bituminous materials after laying and compaction.

The applied methodology resulted in a dynamic model that updates its information package and modifies the output of the analysis every time the data worksheet is integrated with new test results.

A tool as such is intended on the one hand to support the prioritization of any existing Pavement Management System that is currently adopted by administrations to plan maintenance operations on the road network and on the other to provide information as an alert system identifying what does not work in maintenance operations.

BIM systems are therefore destined not only to radically change the paradigms of the real estate market but will be able to make a fundamental contribution to the future of the planet, capable of creating IT models from an architectural, urban, environmental and not simply a single infrastructure point of view but of entire inhabited centers: BIM is at the basis of the creation of sustainable cities and Smart Cities. Not only that, with the help of BIM it will be possible to achieve improvements in terms of more sustainable, inclusive and secure cities.

In this way, the proposed framework can also serve as a decision support tool for better planning and management of smart city infrastructure requirements, taking in account as further perspectives other key factors as energy, estimating/cost simulation and mobility analysis.

Conflict of interest

No potential conflict of interest was reported by the authors.

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