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Can a fully integrated approach enclose the drainage system design and the flood risk analysis?

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Abstract

In recent years, the Building Information Modeling (BIM) methodology has emerged as a pivotal approach for the design and management optimization of infrastructures. The need for fully integrated models has led to develop various tools to support the designers throughout the decision-making process of the entire life cycle of an infrastructure project. In particular, the design of transport infrastructures is a complex process that involves issues concerning all the different fields of civil engineering. In this framework, the BIM method can be efficiently applied to support the project of drainage systems capable of protecting railways and roadways from potential hydraulic risks. According to the above, this study presents an optimized BIM-based methodology for the integrated analysis of the flood risk and the design of the drainage system components. Specifically, the proposed method allows to implement hydraulics and hydrological numerical models as part of the different design phases. Such an approach holds two main advantages for the designer. On one hand, the computational modelling provides a decisive support in both defining water surface profiles over the designed area and identifying the spots exposed to major hydrological risks. On the other hand, the hydraulically guided modelling of each component of the drainage system allows for an increase of the overall productivity and efficiency of the project. A case study is presented to highlight the great potential of the proposed approach in ensuring both the integrity of datasets and the rapid clash detection of critical interferences between each system component. In conclusion, new perspectives about a fully integrated hydraulics analysis in the infrastructures design process are stressed out.

Keywords: Design Tools, Hydraulic Analysis, Hydrology, BIM, Numerical Analysis

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1. Introduction

The Building Information Modeling (BIM) represents nowadays the most powerful methodology for the development of an integrated model able to manage all the information of a project throughout the entire life cycle. The complex nature of the design processes requires the interaction between different involved competences, which is guaranteed by the flexibility and the interoperability of the model.

While the BIM approach has been widely applied in the constructions and building projects (Becerik-Gerber et al., 2010; Bryde et al., 2013; Volk et al., 2014), the documented applications in the transportation infrastructures are still limited (Chong et al., 2016; Kim et al., 2015). Recently, Costin et al. (2018) presented an extensive overview of BIM for bridges, highways and roads, which suggests an increasing interest on the subject. Nevertheless, they also highlight the major state-of-the-art gaps in knowledge and the future challenges for more efficient and cost-effective techniques to build and maintain transport infrastructures. However, many BIM technologies and methods applied in the building industry in the past, have been recently adopted in the transport sector with significant progresses.

In general, the land coverage produced by the construction of a roadway is much greater than that caused by the construction of a building and, consequently, the complex surrounding geophysical environment is severely impacted. To that effect, the design of transport infrastructures requires a thorough knowledge of multiple branches of civil engineering, including the hydraulic and hydrological expertise. Indeed, the design of the drainage and sewage system is an essential part of an infrastructure project. To date, the role of the flood risk analysis and the design of the drainage system components as part of the BIM-oriented model of a transport infrastructure has not been fully debated and only few studies has been developed on the matter.

The emerging benefits of the integration of BIM tools for the stormwater management has been proposed by Ock et al. (2016), who developed a stormwater analysis in a construction site and highlighted the advantages of collecting the discharge point and drainage patterns across the area of interest. Moreover, several works showed the advantages of including the use of BIM oriented software for the flood risk analysis and stormwater simulations in the design phase of hydraulic infrastructures (Kanitkar and Thube, 2016; Nile, 2018; Olson et al., 2010; Shariat et al., 2019). However, the lack of a thorough overview of the advantages and the methodology for the integration of the hydrological and hydraulic analysis requires to be investigated more in depth.

In this framework, the aim of this work is to highlight the advantages of developing a model capable of integrating the hydraulic elements in the design phase, and to define a methodology to fully exploit the potential of a BIM-oriented project. The new Italian regulatory framework (MIT, 2017) for the implementation of digital models requires the introduction of new tools complying with the designers' needs. Accordingly, the BIM-oriented software have to support the traditional design method. The drainage system design has to address the requirements of the new regulatory framework as well, by producing a digital model integrated with all the different expertise of the professionals involved.

In this work, a comparison between the traditional design approach and a new methodology BIM-oriented is presented to highlight the advantages of the latter in the optimization and reduction of costs.

Then, the steps for the definition of the optimized BIM-based methodology are outlined. First, the pipe network is defined as a dynamic object connected to all the other elements that allows for automatic adjustments, thereby eliminating the need for time-consuming manual updates. This enables to have an information exchange between the project elements and the digital terrain model, and to reconstruct the elevation profile of the pipelines relying on the information of the terrain. Secondly, this model assists the designer throughout the decision-making process addressing choices of the best design alternative, by performing analyses and simulations. Moreover, hydraulic analysis can be employed also to verify the risk and improve safety of the infrastructure and all the vulnerable area involved by flood and other natural hazards.

2. Case study

The proposed methodology has been applied to a virtual case study, which served as a benchmark for the determination of advantages and limits of the software used. The project considered is a 2.5 km-long two-lane road, located in the southern Apennines hydrographic district, Italy, in a hilly area characterized predominantly by a natural

drainage system. The considered project interferes with several small water streams and a river, thereby requiring an accurate design of a dewatering and drainage system.
The rainfall characteristics were provided by the pluviometry network of the Italian Hydrographic Service with at least ten years of recorded measurements and the temporal distribution of the rainfall is evaluated by the Intensity-Duration-Frequency (IDF) equations.

3. Hydraulic and hydrologic modeling

Due to their interoperability feature, Autodesk® design tools represent a comprehensive and powerful package among the BIM-oriented software and were used in this work to design and evaluate the hydrologic runoff characteristics and the performance of the stormwater system. In particular:

- Autodesk® Civil3D is a product for civil engineering designs and was used for the design of the road and the components of the drainage system.
- Autodesk® Storm and Sanitary Analysis (ASSA) enables to accurately model the hydrology and hydraulics of a project with different method, including the rational method, the US soils conservation service (USDA, 1964, SCS TR-20 and SCS TR-55) method and the HEC-1 package. The conservation of mass and momentum equations are implicitly solved by ASSA to determine the runoff, velocities and water levels in the drainage network of channels and pipes. The use of ASSA has been coupled with Autodesk® Analyze Gravity Network (AAGN) a useful wizard for the analysis of the flow through the pipes and the evaluation of the energy and hydraulic grade lines. The computations are based on the Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22 (HEC-22, 2013).

4. Methods

4.1. State of the art

The dewatering and drainage systems of roads and highways is of paramount importance in transport infrastructure designs. However, due to the relatively simple rainwater collection system adopted in the practice or the small discharges involved, the design of these elements is often considered of minor importance, but it cannot be overemphasized. In fact, drainage problems caused by an inadequate rain water management will adversely affect the integrity and functionality of the transport infrastructure and possibly expose it to main natural hazard.

The primary purposes of a road drainage system are:

- to remove the rainwater from the surface of the road in order to avoid risk of vehicles skidding or aquaplaning on the surface water;
- to manage the interactions between the transport infrastructure and the stream network in the surrounding area.

  To this effect, the design must prevent the disruption of water bodies and include bridges or culverts.

The design of a drainage system is thus composed of the following elements:

- cross fall and impermeable road surface materials;
- outlet ditches, side ditches and collector pipes;
- culverts.

Moreover, the interactions between the road construction and the surface drainage pattern in the watershed must be properly evaluated. In fact, it is fundamental to clarify the currents condition and to estimate the flood discharges along the road alignment and in the most vulnerable locations, such as river crossings. A hydrological study is in fact mandatory by requirement of the Italian Ministry of Infrastructures and Transports to verify the feasibility of the project.

Traditionally, the geometrical design is a cumbersome, time-consuming process, which requires several analyses and calculations. Typically, the design engineer has to create the drainage system alignment along the road and define the road profile using coordinates, stations and elevations. The drainage basin has to be defined manually by the uphill contour lines which marks the watershed. The runoff flow rate for the outflow section is determined and, consequently, it is possible to design the pipe diameter through an iterative process, in order to find the optimum while satisfying the design standards and constraints. This process requires for multiple repeated adjustments of the project draft and technical drawings, resulting in a considerable loss of time.

In view of the above, it is clear that a BIM oriented approach would allow for the management of the involved complexity with the final aim of guaranteeing the accomplishment of the headline targets with an optimized strategy.

4.2. Proposed methodology

A new workflow is herein proposed to optimize the design process and to produce a new digital information model.

A schematic representation of this approach is displayed in Fig. 1, where the main goals are included and described as follows:

1. A Basemap is reconstructed to collect the background data and establish a framework for the project inclusion. These files can be included as external references and technical drawings and are also available as Web Map Service (WMS), Web Feature Service (WFS) and Shape (SHP) connection from the national authorities responsible. The project has to be properly geo-referenced in order to be possibly coupled with GIS data.
2. A Parts List has to be created simultaneously, which enables to insert all the elements of the project (i.e. pipes, manholes and structures). The Country kit can be used to define the geometries and the properties of each component (style, rules, render material, pay items etc.) by accessing the catalog of existing items or using the Country customized tool palettes.

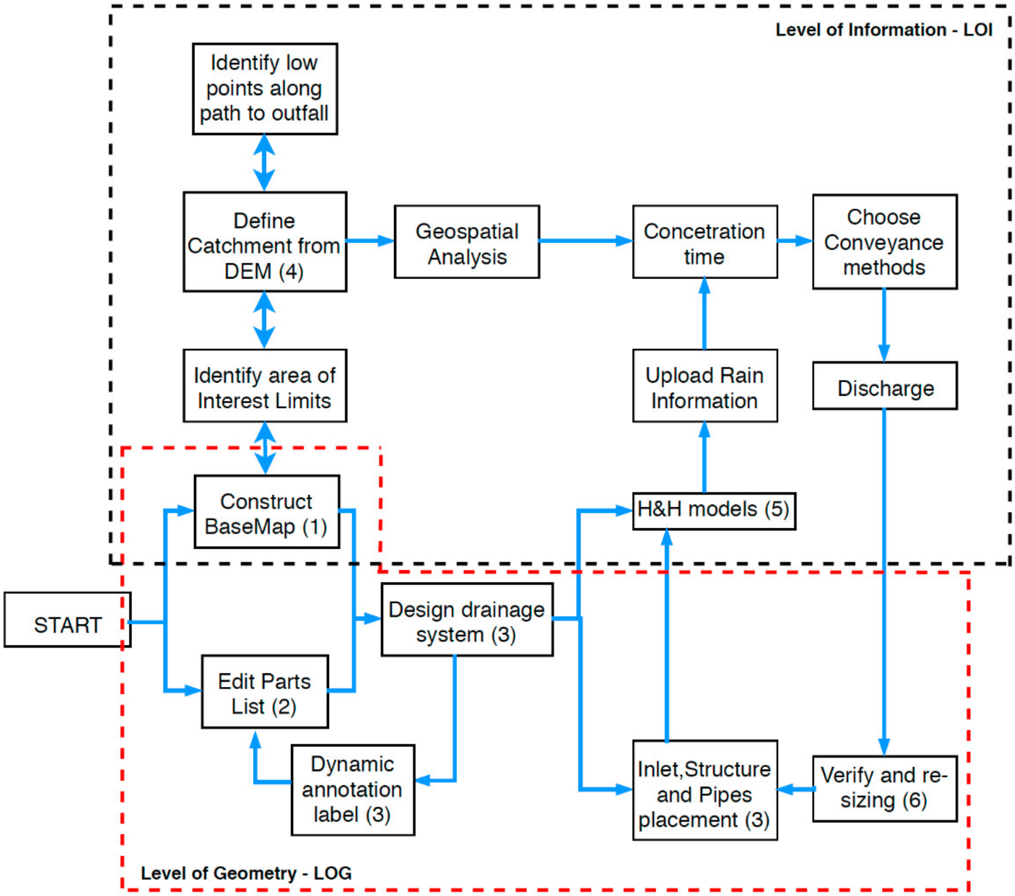

Fig. 1. Schematic workflow of the proposed methodology to implement a digital model for the drainage system design.

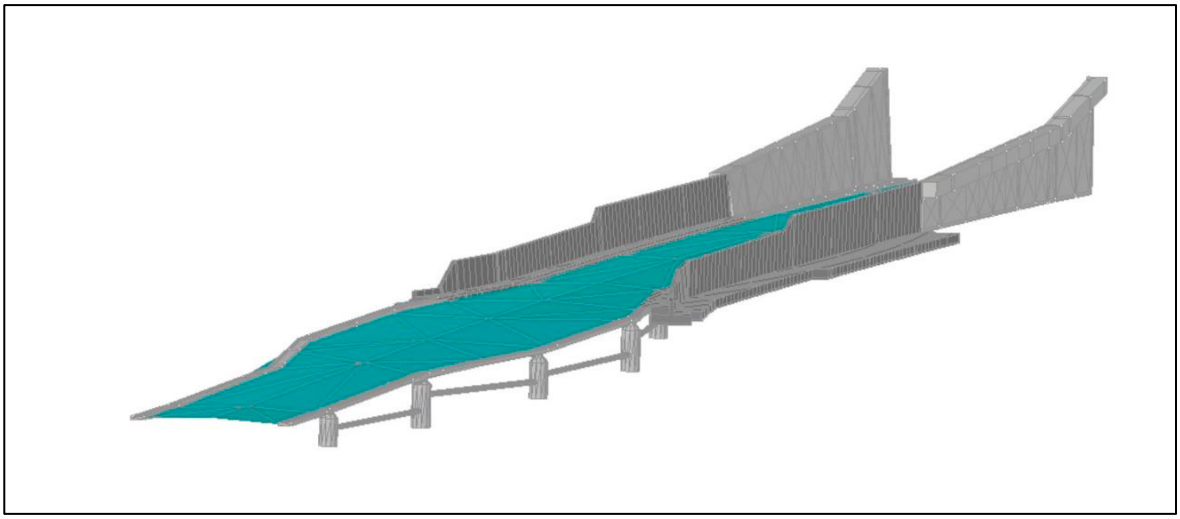

Fig. 2. Extracted solids from Civil 3D corridor of the case study road segment.

In Fig. 2 the extracted solids from a segment of the corridor of the case study road are shown.

3. The components of the system are defined as dynamic objects interacting with the digital terrain model. This feature is typically used for the road alignment and is extended to the drainage system. This interoperability enables to collect automatically the rim elevation based on the existing elevation of the ground, which can be used for the design of the proper drainage components. The labels and tables are easy to access and to update. In particular, between all the BIM-oriented software, Civil 3D enables to modify and custom specific labels, constantly updated after any change and to create several object variables, operators and mathematical functions, which can be used to write specific expressions.
4. With ASSA it is possible to implement detailed analysis on the surface elevations, rapid definition of the drainage basin, sub-basin and narrow regions which are used to define the stream network and flow direction. The In Fig. 3, the slope analysis performed on a corridor surface with Civil 3D is shown and was used to identify the inlets location. The drainage basin morphology is dynamically analyzed in this environment by means of a hydrological approach, inspired to the Horton Machine developed on GIS. At the end of this process, the basin can be considered as a dynamic object which is connected to all the other objects in the model. The alignment of the drainage system and each component previously selected in the Parts List are drawn in the model. At this stage it is possible to associate the drainage basin to each elements of the system and to define the conveyance method for the analysis of the runoff discharge. The vertical alignment of the project is effectively produced together with the terrain elevation profile. In this way is possible to simultaneously derive the earth-moving and define the best project alternative.
5. ASSA includes many features out of the box for the hydraulics and hydrology (H&H) needs. Depending on the components of the hydraulic infrastructure that has to be designed, many tools are available to analyze and verify the hydraulic conditions. It is thus possible, while defining the geometries, to simulate complex hydrological processes in time and space, accounting for the infiltrations, evapotranspiration, snow melting, and sub-surface drainage.

   Although in the past years dedicated software were developed to run such simulations, the advantage of this new approach lies in the integration between the numerical modeling and the geometrical components of the design. A real bi-directional integration can be established since the results of the hydraulic analysis (i.e. flow rates, velocities, water depths) provide a new informative attribute in the network which contributes to the Level of Development (LOD), as defined by UNI 11337-4.

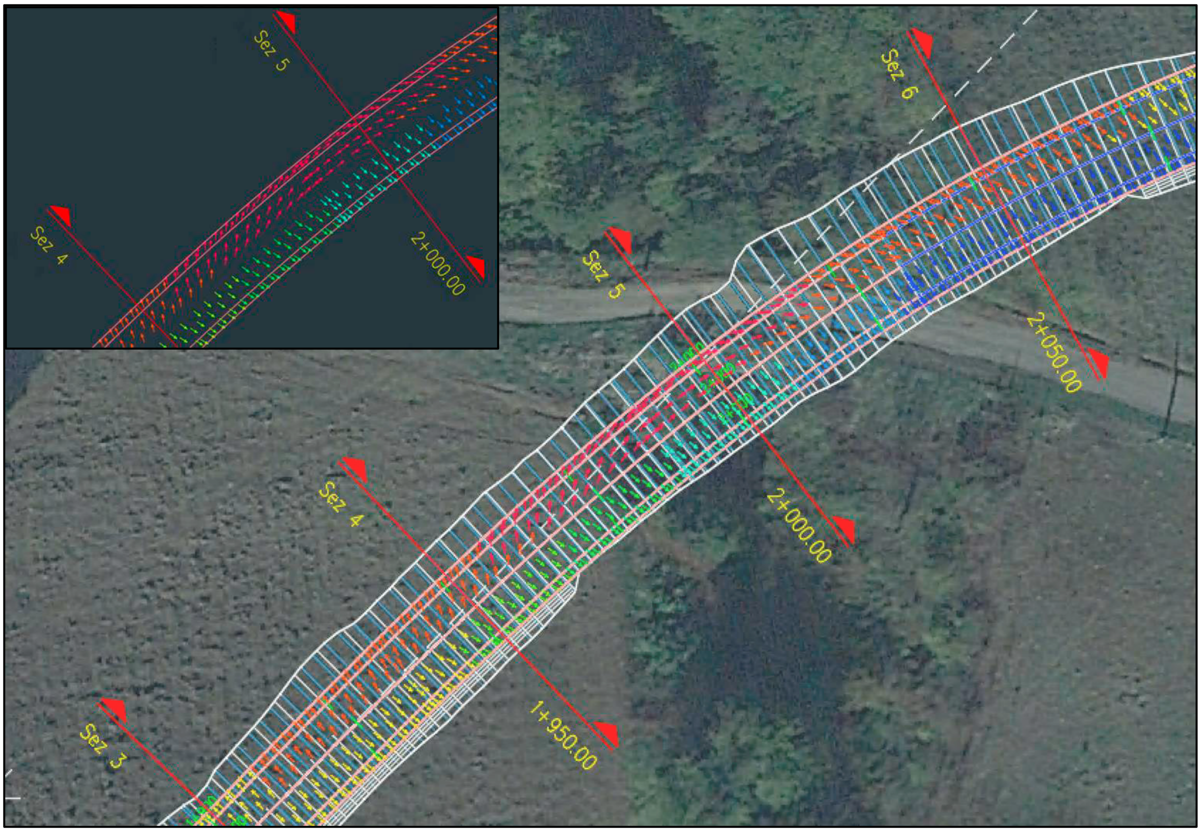

Fig. 3. Slope analysis performed on the corridor's surface to identify the right position of the inlets.

The rainfall intensity provided by the Intensity-Duration-Frequency (IDF) curve of the Hydrographic Service recordings can be uploaded as .csv or .idf file. This information can be coupled with the characteristics of the catchment basin in terms of runoff coefficient, area and averaged elevation, to evaluate the time of concentration at the outlet section. In this way is possible to determine the flow rate attributed to each components of the drainage system in the network. The obtained results are verified and contribute to the definition of the attributes of the elements.

6. The analyses perfromed enables to implement a rapid check of the hydraulic and hydrological conditions of the system within the model and to resize and reconsider the designed components to improve the overall functionality.

5. Results

As a result, the application of the proposed methodology to the case study was useful to stress out the relevant advantages and limitations.

A comparison with the traditional methodology highlights that the BIM methodology improves prompt response to change with faster processes. A reduction in project errors, rework times and project duration is thus observed compared to the traditional design approach. In particular, the method was found to be effective in the design of the components of the drainage system which were verified and updated within the model with a significant reduction in times. The link between the project design and the simulations, is above all the most useful benefit of the integrated process herein proposed. In fact, in the case study proposed, the software used not only represented a valid design tool, but were also used for the hydraulic and hydrological analysis on the drainage components network.

Consequently, this process led to an increased awareness of the design choices and alternatives. On the opposite, the methodology turned out to be less effective in the integration of the flood risk analysis and definition of the inundation mapping area within the design environment, which will be deepened in a further application.

Finally the research aimed to point out that the BIM methodology or more in general the application of software which combine the Computer-Aided Drafting (CAD) to the Computer-Aided Engineering (CAE) for the project of the drainage systems, is a great instrument during the design phase to ensure the safety conditions of the transport infrastructure. In particular an inappropriate design of the elements componing the drainage system, could led to early structural failures and increase the risk of accidents. The proposed methodology gives the opportunity to tests different triggers and simulate the impact of advarse scenarios on the drainage system with the final aim of guarantee the safety conditions and defining the best alternative.

6. Further application and challenges

The described methodology enables to apply a hydraulic and hydrological study to a transport infrastructure, but it can be extended to several different applications, such as the flood risk analysis and the rainwater pollution prevention. Depending on the project and the surrounding environment, the design of a drainage system is an essential part for the prevention of flood events. The implementation of appropriate actions to enhance the flood prevention is pivotal to reduce the exposure of people and property to flood hazards and eventual economic losses.

In the recent years the US Army Corps of Engineering developed HEC-RAS-Georas (Murachelli and Riboni, 2010), which couples advanced hydraulic analyses with the digital terrain models (DTM) and shape files produced by the GIS instruments. Autodesk® provides a sophisticated software package to support the HEC-RAS analysis called Autodesk® River and Flood Analysis Module, which can implement the flood risk analysis and the evaluation of the inundation mapping area right in the project model. This allows the designer to verify the interferences between the project area and the river basin and to verify the water surface profiles at the infrastructure watercourse crossings. One of the main advantages of the use of Autodesk® packages implementing HEC-RAS analysis is the possibility to automatize the extraction of the river cross-section. To date, this package implemented in Autodesk®, needs further improvements to be actually competitive with the traditional analysis method in HEC-RAS, as it does not include all the software capabilities

Concerning potential further applications, the use of this methodology can facilitate the development of rainwater pollution prevention plans, which is a frequent phenomenon in construction site areas where a variety of chemical products are used. The United States experience certifies this attention in the design of drainage networks. In fact, in the U.S., construction sites that interfere with an area of dimensions above one acre, are regulated under specific program. In order to identify the run off the rainwater pollution flow paths, the slope analysis can be conducted using ASSA in Civil 3D from the elevation data, pipe network and soil type information. The most considerable benefit of BIM tools for the development of the Best Management Practices (BMPs) at constructions sites with the aim to increase productivity at the beginning of construction progress is that contractors or designers can easily analyze run off at projected sites.

7. Conclusions

In the present work, the advantages of an optimized BIM-based methodology for a comprehensive hydraulic and hydrological analysis and design of the drainage system components have been discussed. The methodology presented was applied to an ideal case study of a 2,5 km long two-lane road in the Apennines hydrographic district, Italy. In this research, Civil3D, ASSA and AAGN have been used to perform the simulations, to design and verify the hydraulic conditions of each component of the system. This study attempts to present an optimized approach to include the design of a drainage system in the digital model of a transport infrastructure, and to highlight the advantages with respect to the traditional time-consuming approach. An accurate way to examine the relation between the design of the components of the drainage system and hydraulic analysis in the catchment basin is proposed. Many rainwater storm software and simulation model exist, but the advantage of this model is to include all the information in a connected environment where the hydraulic analysis and the design coexist. However, further efforts to make this approach more competitive needs to be conducted and an attempt to extend this model to different scenarios and for the definition of the flood risk analysis and rainwater pollution plans may be considered.

In conclusion, the results indicate that the integrated design of the drainage system in a digital model, along with the hydraulic and hydrologic analysis leads to a more accurate and optimized model and reduces significantly the time required for the traditional design approach.

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