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OPTIMIZING ROAD INFRASTRUCTURE DESIGN USING I-BIM TECHNOLOGY

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Abstract

Infrastructure Building Information Modeling (I-BIM) has emerged as an important supporting technology for managing infrastructure project design, construction, and operation. This paper presents the development of an I-BIM model that can holistically capture the components and their integration characteristics of a road project. Extending previous works, the development deems to provide detailed road design analysis including drainage, signage, and lighting, traffic lanes of variable width, inclined pavement layers, vegetation and plantation, etc. In addition, the difficulties in developing "irregular" components and aligning them with each other and with the longitudinal land terrain are examined. The development applies to a real-world road design to explore the applicability potential.

Introduction

Transport infrastructure projects, being large scale engineering ones, require significant capital investments for their construction and maintenance, in return to multiple benefits for the users and the society out of their operation (Timilsina et al. 2020). In fact, they are quite important projects playing a key role in the social and economic development of regions and countries, often echoing the economic and technological development of them (Cigu et al. 2019).

The continuous improvement and application of new methods to improve the design and operation of such projects is always a goal (Costin et al. 2018). Considering the potential and positive effect of applying BIM technologies in construction (Wong and Fan 2013), the application and use of such tools in infrastructure project management could provide an effective method to increase efficiency during the project life cycle.

In large scale infrastructure projects, cost overruns, completion time overflow, wastefulness, and performance loss constitute conventionality rather than exception (Love et al. 2014). Engineering challenges - arising mainly from the specificities of such projects - exhibit a wide variety in terms of structural, geometrical, and mechanical characteristics. On the other hand, such projects are spawned by various multidisciplinary groups (architects, engineers, contractors, operators, etc.) having different (and often conflicting) priorities and objectives at every project phase. As a result, there is a large volume of information, generated from start to finish, subject to managing deficiencies and performance degradation.

Liu et al. (2017), after studying the most important risks in engineering projects through a questionnaire shared with 500 construction companies, noted that project performance - in terms of time, cost, quality, and safety - is significantly affected by the design team capability, the information accuracy, and the design associated delays. Undoubtedly, all the above factors contribute to problems and risks that infrastructure projects face nowadays and in the past. The root cause, according to Flyvbjerg (2013), is the fact that project planners tend to systematically underestimate or even ignore project complexity risks during the project development phase and decision making. Thus, many problems are associated with project design (or communication about the design), while modifications made alongside the way are related to deficiencies or omissions by the design.

As a result, both the productivity and the efficiency of the projects remain modest (Agenda, I. 2016). In this context, the traditional ways for managing infrastructure projects cannot meet the challenges of today, where construction is becoming more and more complex and demanding, and these projects require adequate planning and prudent resource management. Teizer (2015) stresses that key issues in the direction of improving infrastructure project management include schedule obedience, material procurement, supply chain-related actions, project status control, safety and quality monitoring. Furthermore, as Chi et al. (2012) state, during the evolution of a project, interim and ad hoc works arise. Because of this, the design of such temporary works does not always receive the attention and control levels that are typically required. Therefore, these elements should be integrated within the design, construction performance and safety parameters.

The introduction and use of BIM technology in the construction industry has assisted in automating traditional processes, manifesting positive effects in quality and productivity (Ullah et al. 2019). In addition, the adoption of BIM has significantly contributed to the digital transformation of the general industry, moving from the traditional way of designing and planning typical construction projects (e.g., buildings) towards a digital ecosystem that includes 3D visualization and real-time communication. Instead, in large infrastructure projects, the application and adoption level of BIM technologies is lacking behind, resulting in lower productivity and efficiency outcomes.

In recent years, there have been steps forward in the application and use of BIM in the infrastructure sector, as the benefits of 3D modelling and the use of smart objects are increasingly recognized (Tang et al. 2020; Cantisani et al. 2022). A 3D/BIM model is not limited to the geometric and design features visualized in the simulation (Gould 2010) but it is like a digital simulation model of the actual structure, whose properties and features are fully configurable. Thus, BIM technology is a reliable design tool that provides access to a comprehensive set of knowledge about the form, materials, environment, technical characteristics, costs, etc. of the project.

Despite the numerous benefits of I-BIM and the development of implementation strategies, the application of this technology remains limited, and the overall effectiveness of BIM in real projects has not been fully studied. Therefore, there is a need to explore the practical application of Infrastructure BIM (I-BIM) technology in the planning and design of projects. In this paper, the development and description of such a system for road projects is presented and discussed.

Infrastructure BIM

The development of road infrastructure projects involves two phases, the design and the construction ones. There are several sub-stages, in which plans and documents are produced, relating, among others, the technical specifications of the design, the cost and the duration of the construction.

In the traditional approach, communication among stakeholders has been largely fragmented and based on the exchange of 2D drawings and documents. As a result, coordination is particularly difficult, as much information (data) is lost or miscommunicated in the transition from stage to stage, often leading to the need for re-creation. Further, in large-scale projects, there are always large volumes of data and, likewise, it is difficult to communicate and present them correctly. Consequently, data omissions or miscommunication lead to inaccurate information sharing among participants and project phases. As such, when errors are detected through the several steps, the project has already progressed making any needed intervention difficult, costly, time consuming, and often of inadequate effectiveness.

In contrast, in infrastructure BIM (I-BIM) management, the information flow is coordinated in real time so that the work execution can be carried out by all involved parties (of different branches) effectively, as the digital simulation of the construction is up to date to the needed modifications and project progress monitoring. Thus, decision making for changes can be carried out in the early stage where the cost of changes is low and their effectiveness is high. Hence, more efficient collaboration is achieved by all groups involved in all phases throughout the project life cycle, eventually leading to an effective design and construction decision making.

Methodology

I-BIM provides a comprehensive 3D visual database and modeling of the project under development, integrating a range of data, including 3D terrain models and road design elements, such as road geometric design, cross-sections, measurements, electromechanicals, hydraulics, and more. This allows for the effective design of road systems and the optimization of project outcome. By integrating more data into the existing 3D model, i.e., work scheduling and construction cost, project managers can validate road project conformance to standards before construction commencement, leading to enhanced project efficiency and effectiveness. Therefore, the use of I-BIM in the initial design phase of large and complex horizontal geometry projects, can significantly contribute to different scenarios evaluation by providing visual, qualitative, and quantitative information that helps in the direction of selecting the best scenario that minimizes the time and cost and improves the quality of the work.

The design methodology of the road project through I-BIM includes the following steps, in accordance with the conventional way of doing things:

- Capture the terrain surface along the road alignment.
- Model the road and its individual elements (road deck, positions of sidewalks, roundabouts, islands, crossings, overpass bridge).
- Visualize the core road elements and layers in a 3D representation.
- Model and present secondary road elements that are necessary for road operation (signs, lighting fixtures, planting objects, etc).

Unlike traditional techniques and programs, all elements and characteristics of the project are present in a single 3D/I-BIM model. This enables the visualization of the road design in a realistic environment, which is helpful in identifying any potential conflicts that may arise. Most importantly, alternative design scenarios can be easily simulated and evaluated to realize the best layout solutions. Further, the I-BIM technology facilitates collaboration among the design team members by allowing them to access and modify the single digital model in real-time.

Interoperability and data standardization, using openBIM technology and Industry Foundation Classes (IFC), are vital for efficient information exchange among different stakeholders in the construction process. In this direction, the IFC 4.3 format is a significant step toward automating and optimizing facility management within the project lifecycle. In the road design study, interoperability helps transferring topographical mapping from AutoCAD Civil 3D to Revit for further processing and enhancing decision-making and stakeholder communication in project design.

Case study

As part of the development, this work presents as a case study the employment of the I-BIM technology to the design of the new ring road in Nemea (Greece). The 3D modeling of the road and its elements (road surface, sidewalk, roundabouts, electric lighting, technical works, etc.) has been realized using the AutoDesk REVIT software. Such kind of software have been developed with an initial focus on building design and construction, at least in construction industry applications. It appears, however, that they can effectively be used for other types and large-scale projects.

The terrain design of the area has been based on topographic CAD diagrams, which are first adjusted to their actual dimensions during modeling in REVIT. The adoption of BIM in this project has largely focused on design activities. The existing road passes through the urban area of the city of Nemea, as shown in Figure 1. As a result, traffic congestion is observed within the city that results in increased travel times and accident risk. The latter is more evident at an intersection where the new road is going to commence, in which case the intersection angles of the current geometry of the converging roads provide very poor visibility conditions (Figure 2). The bypass follows a new alignment, totaling 1.4 km, starting at location (1) and ending at location (2), as shown in Figures 2 and 3. The new road design includes two roundabouts at its ends to ensure high safety conditions and smooth traffic flow.

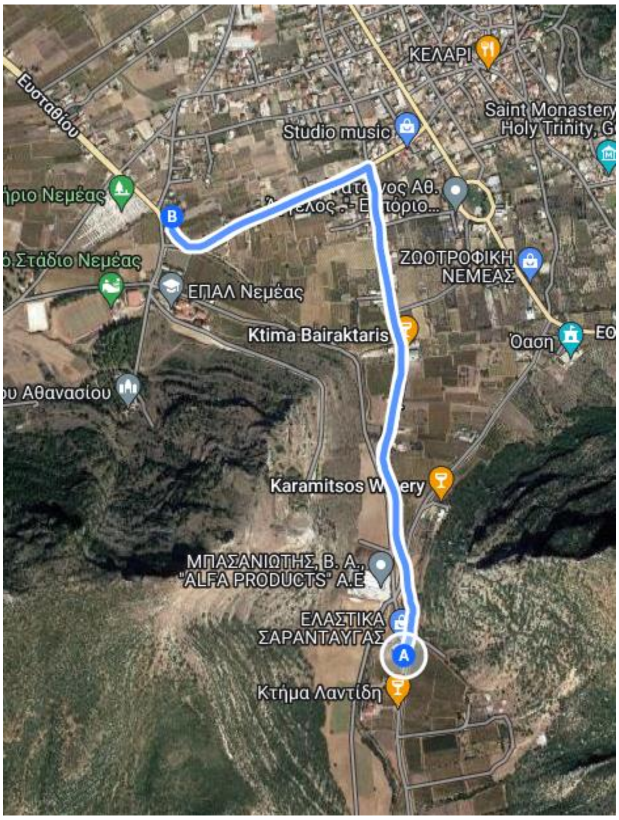


Figure 1: Existing road through the urban area

To select the optimal layout, several design alternatives have been developed and evaluated along the land zone around the potential layouts, with special emphasis to the roundabouts that link the ring road with the existing road segments. The proposed layout is shown in Figure 4.

The new road design features a nominal speed $V_e = 60$ km/hr, horizontal radius of $R \geq 140$ m, and maximum longitudinal gradient 3.80%. The road consists of two lanes (one per direction) with an effective road width of 7.00 m plus 2.00 m of sidewalk. Further, at the roundabout access sections, appropriate widening of the roadway is designed. Along the entire length of the road, guard rails of 0.60 m in height have been laterally designed in both directions.

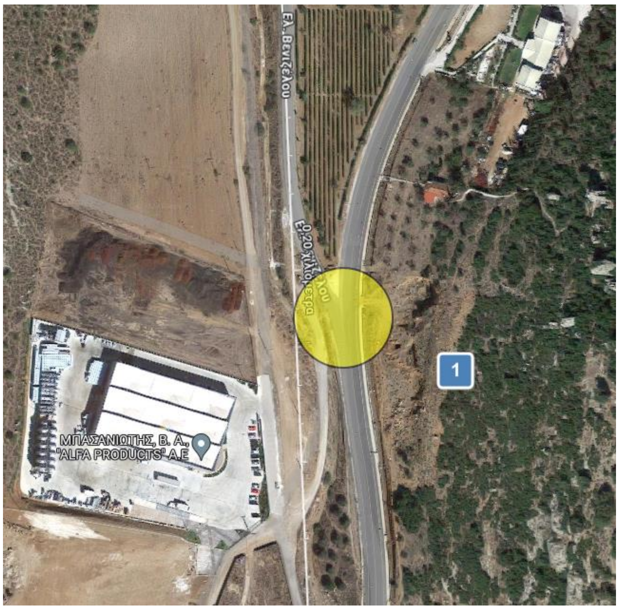


Figure 2: A high accident risk segment of the existing road design (point 1, same as point A in Figure 1)

The full project model, encompassing all the information, is depicted in Figure 5 and allows efficient project analysis and management. As stated before, the utilization of such a model facilitates the effective management of changes at any project component (e.g., drainage system) and the direct communication of such changes at all management levels and stakeholders.

The cross-section of the carriageway comprises multiple layers that include (from the lowermost to the uppermost level): two layers of sub-base of 10 cm thickness each, two layers of base of 10 cm likewise, asphalt pre-coating, asphalt base layer of 5 cm thickness, asphalt adhesive coating, asphalt traffic layer of 5 cm thickness, asphalt adhesive coating, and asphalt anti-slip layer of 4 cm thickness. All layers have been simulated in the 3D/BIM model (Figure 6).

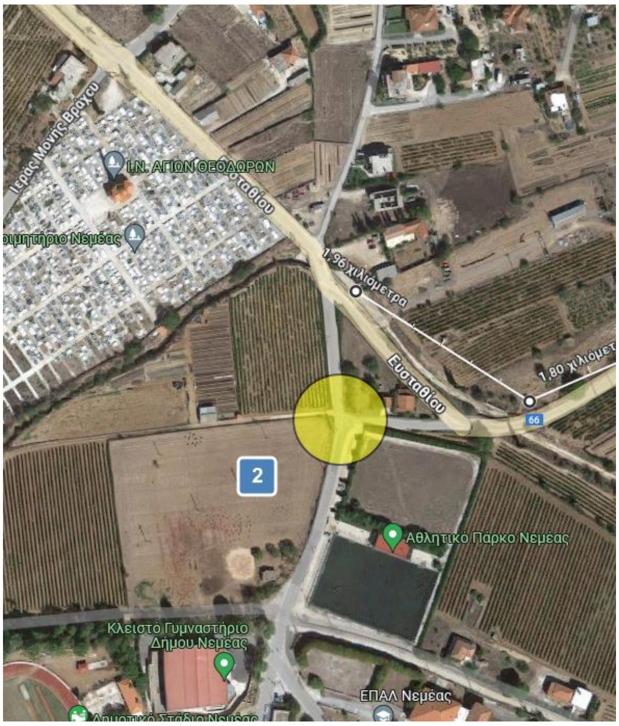


Figure 3: Endpoint of the ring road (point 2, same as point B in Figure 1)

Figure 4: Ring road alignment design

The design of the roundabouts has been carried out in accordance with the "Geometric Design of Highways and Streets" (Hancock et al. 2013) and "Roundabouts: An Informational Guide" (Robinson et al. 2000). The proposed roundabout layouts allow for convenient and safe pedestrian and vehicle access on the ring road. Figures 7 and 8 display the configuration of roundabouts 1 and 2 respectively. To reinstate the connection with local roads, two level junctions (N1 and N2, in Figure 5) have been designed. The junctions, as they have been designed and simulated in the 3D/BIM model, are illustrated in Figures 9 and 10 respectively.

Horizontal and vertical signage has been designed and installed along the entire length of the road to guide the drivers and effectively regulate the traffic. An indicative case is shown in Figure 11 for roundabout 2.

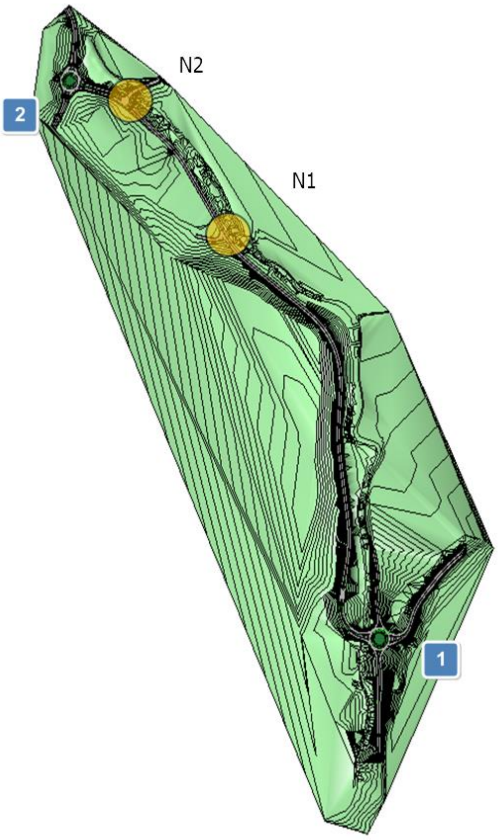


Figure 5: 3D/BIM model of the ring road

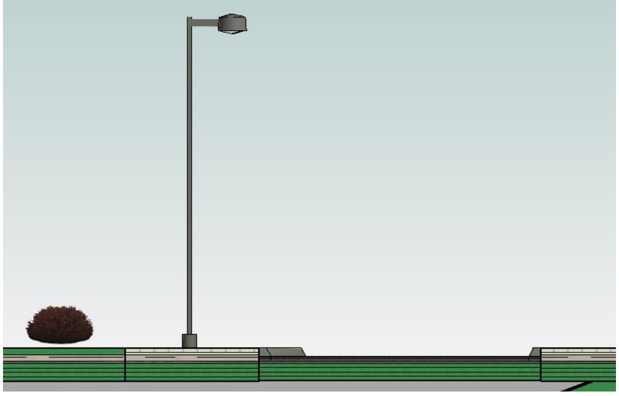


Figure 6: Cross section of pavement layers

Figure 7: Visualization of roundabout 1

Figure 8: Visualization of roundabout 2

Figure 9: Visualization of road junction N1

Figure 10: Visualization of road junction N2

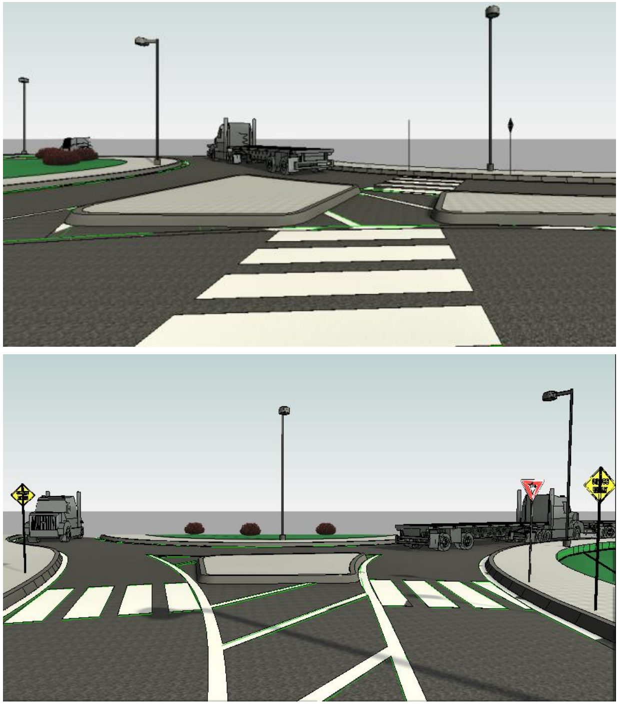


Figure 11: Horizontal marking and vertical signs at roundabout 2

Further, road lighting design has been performed through the 3D/BIM model, which pointed that a total of 51 luminaires of 150-Watt power and 16,100 lumen luminous flux are required to be installed. Figure 12 indicatively presents the electric lighting scheme at the roundabout 2 zone.

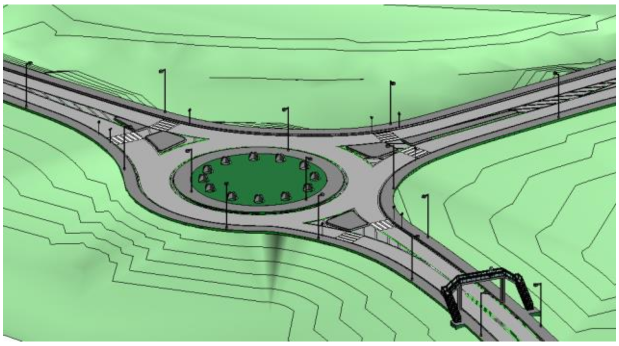


Figure 12: Electric lighting system in roundabout 2.

Analyses and cost estimation of the project have been carried out through the I-BIM model. The estimates can be either for single elements or groups of elements of the project. As an example, the costs for signs and for railings are presented in Tables 1 and 2 respectively, as reported by the software. Similar tables have been developed for all project components. Considering typical unit cost values for Greece, a total cost of 2.32 million € has been estimated for the whole project construction.

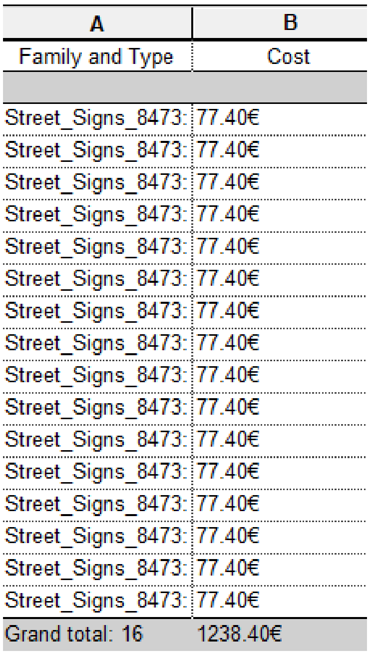
Discussion and Conclusions

This study describes the potential and advantages of BIM technology in the design of large infrastructure projects, in this case the ring road of Nemea city in Greece. Opposite to the common belief that BIM technology is mainly applicable to buildings, it can be proven to be equally applicable to infrastructure projects. In this work, I-BIM simulation is particularly effective as it combines parametric 3D simulation and high-level information codification to create a virtual digital model of the project, the 3D/BIM multi-level model, the use of which highly improves the processing, design, planning and management of the project construction and operation.

The importance of using BIM technologies is undoubtedly related to participant coordination and information sharing, the identification and resolving of conflicts at early stage or the evaluation of alternative design solutions. These aspects of BIM tools are rather well known and not widely discussed in this paper. The main goal of this work is to dig into the details of a road infrastructure project and explore whether BIM software can represent them in an integrated way for the design, construction, operation, maintenance, and management to increase interoperability. In addition, the difficulties and barriers in developing the I-BIM model of a project with “irregular” components and in aligning the different elements with each other and with the longitudinal land terrain are explored.

The work outcomes indicate that the project design through Revit (or any other BIM software) is feasible to a high detail, increasing interoperability and allowing all designers to have access to updated project plans at any time and to work collaboratively, thus significantly reducing effort and errors in design. In addition, the 4D and 5D representation of the project, through the time and cost showcase, provides aforehand information on the expected project progress and cost evolution and enhances decision-making and stakeholder communication during construction, leading to higher quality at lower cost.

Table 1: Cost estimate for signs



A	B
Family and Type	Cost
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
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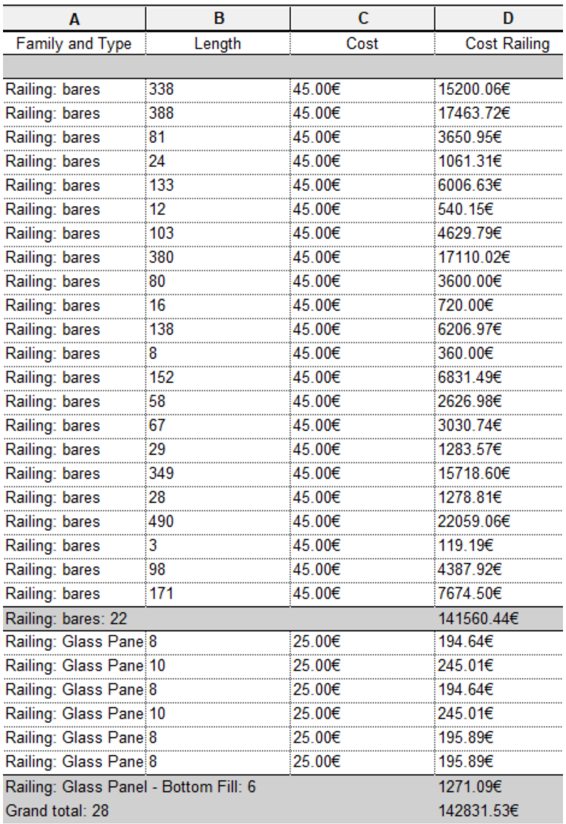
Street_Signs_8473:	77.40€
Street_Signs_8473:	77.40€
Grand total: 16	1238.40€

Table 2: Cost estimate for railings



A	B	C	D
Family and Type	Length	Cost	Cost Railing
Railing: bares	338	45.00€	15200.06€
Railing: bares	388	45.00€	17463.72€
Railing: bares	81	45.00€	3650.95€
Railing: bares	24	45.00€	1061.31€
Railing: bares	133	45.00€	6006.63€
Railing: bares	12	45.00€	540.15€
Railing: bares	103	45.00€	4629.79€
Railing: bares	380	45.00€	17110.02€
Railing: bares	80	45.00€	3600.00€
Railing: bares	16	45.00€	720.00€
Railing: bares	138	45.00€	6206.97€
Railing: bares	8	45.00€	360.00€
Railing: bares	152	45.00€	6831.49€
Railing: bares	58	45.00€	2626.98€
Railing: bares	67	45.00€	3030.74€
Railing: bares	29	45.00€	1283.57€
Railing: bares	349	45.00€	15718.60€
Railing: bares	28	45.00€	1278.81€
Railing: bares	490	45.00€	22059.06€
Railing: bares	3	45.00€	119.19€
Railing: bares	98	45.00€	4387.92€
Railing: bares	171	45.00€	7674.50€
Railing: bares: 22			141560.44€
Railing: Glass Pane	8	25.00€	194.64€
Railing: Glass Pane	10	25.00€	245.01€
Railing: Glass Pane	8	25.00€	194.64€
Railing: Glass Pane	10	25.00€	245.01€
Railing: Glass Pane	8	25.00€	195.89€
Railing: Glass Pane	8	25.00€	195.89€
Railing: Glass Panel - Bottom Fill: 6			1271.09€
Grand total: 28			142831.53€

Unlike typical building design, in which components are of “regular” (e.g., rectangular) shapes, infrastructure project design presents extensive challenges in terms of irregular component shapes, material and manufacturer specificities, and component alignment needs within an integrated design. For example, pavement layers need to be aligned among them and along the road sections (e.g., joins at main road and entrance/exit sections or road approaches and roundabouts). Conflict resolution needs also to be addressed in reference to the road design adjustment to landscape, the incorporation of drainage system, the pavement cross-section design at curved parts of the road, based on large-truck trajectory analysis, etc. The BIM-software database often needs to be enhanced with specific road design elements and potential vendor information, e.g., horizontal and vertical signage, lighting, vegetation and plantation, etc.

In the present work, the design dives into greater detail, in comparison to previous works, indicating the feasibility potential of such a design. However, some limitations should be expected in practical applications. A main difficulty refers to the exact fitting of the road to the landscape, which is mainly due to the inaccuracies or approximations in the digital representation of this landscape. Another challenge is related to the effective placement of overlapping layers of components that are curved and inclined in the longitudinal and transverse directions (e.g., pavement layers). This can be done by considering smaller sections of uniform shape, which are then aligned at their joins and integrated to the full model.

The I-BIM technology can be successfully used in the design and management of large-scale infrastructure projects. In road projects, in particular, the design can improve traffic flow and safety as well as contribute to drainage, signage, lighting, and aesthetic upgrading. The use of BIM technology in large infrastructure projects reduces the effort required during design and construction, while offering effective tools to manage cost and completion time, to reduce waste, and to improve construction quality performance.

References

Agenda, I. (2016). Shaping the future of construction, a breakthrough in mindset and technology. In World Economic Forum.

Cantisani, G., Panesso, J. D. C., Del Serrone, G., Di Mascio, P., Gentile, G., Loprencipe, G., & Moretti, L. (2022). Re-design of a road node with 7D BIM: Geometrical, environmental and microsimulation approaches to implement a benefit-cost analysis between alternatives. Automation in Construction, 135, 104133.

Chi, S., Hampson, K., & Biggs, H. (2012). Using BIM for smarter and safer scaffolding and formwork construction: a preliminary methodology. In Proceedings of the CIB WO99 International Conference on Modelling and Building Health and Safety 2012 (pp. 64-73). Department of Building, School of Design and Environment, National University of Singapore.

Cigu, E., Agheorghiesei, D. T., Gavriluță, A. F., & Toader, E. (2018). Transport infrastructure development, public performance and long-run economic growth: a case study for the Eu-28 countries. Sustainability, 11(1), 67.

Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure–Literature review, applications, challenges, and recommendations. Automation in Construction, 94, 257-281.

Flyvbjerg, B. (2011). Over budget, over time, over and over again: Managing major projects. The Oxford Handbook of Project Management, 321-344.

Gould, L. (2010). What is BIM… and should we care?. Construction Research and Innovation, 1(2), 26-31.

Hancock, M. W., & Wright, B. (2013). A policy on geometric design of highways and streets. American Association of State Highway and Transportation Officials: Washington, DC, USA, 3.

Liu, J., Xie, Q., Xia, B., & Bridge, A. J. (2017). Impact of design risk on the performance of design-build projects. Journal of Construction Engineering and Management, 143(6), 04017010.

Love, P. E., Sing, C. P., Wang, X., Irani, Z., & Thwala, D. W. (2014). Overruns in transportation infrastructure projects. Structure and Infrastructure Engineering, 10(2), 141-159.

Robinson, B. W., Rodegerdts, L., Scarborough, W., Kittelson, W., Troutbeck, R., Brilon, W., ... & Mason, J. (2000). Roundabouts: An informational guide (No. FHWA-RD-00-067; Project 2425). United States. Federal Highway Administration.

Tang, F., Ma, T., Zhang, J., Guan, Y., & Chen, L. (2020). Integrating three-dimensional road design and pavement structure analysis based on BIM. Automation in Construction, 113, 103152.

Teizer, J. (2015). Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites. Advanced Engineering Informatics, 29(2), 225-238.

Timilsina, G. R., Hochman, G., & Song, Z. (2020). Infrastructure, economic growth, and poverty: A review. World Bank Policy Research Working Paper 9258.

Ullah, K., Lill, I., & Witt, E. (2019). An overview of BIM adoption in the construction industry: Benefits and barriers. In 10th Nordic Conference on Construction Economics and Organization, Emerald Publishing Limited, 297-303.

Wong, K. D., & Fan, Q. (2013). Building information modelling (BIM) for sustainable building design. Facilities, 31(3/4), 138-157.

Appendix: Layers in the 3D/VIM model (design phases)