New 3D BIM modelling methods for road and rail infrastructure

Matjaž Šajn, M. Sc. Civil Eng., CEO,
Leon Leban, Product Manager,
Klemen Ozimek, Bs. Civil. Environ.,
Petra Tihole, M. Sc. Civil Eng.,
CGS Labs d.o.o.

Summary

The new Slovenian Construction Act introduces the obligation of a BIM design for all publicly funded projects of public interest. This poses a particular challenge for civil infrastructure designers, as BIM design requires specialist knowledge and appropriate software. At CGS Labs, we are developing new methods and approaches for 3D BIM modelling of road and rail corridors, which results in software that eases the time-consuming and complex work for designers. The paper describes the theoretical basis and practical approach of BIM modelling for different project design approaches. The development of these methods is supported by the knowledge and experience gained by the authors of the paper in their long-standing work in the field of digitisation of the built environment.

New methods of 3D BIM modelling of road and railway infrastructure

Abstract

The new construction law brings an obligation to implement BIM planning in all projects of public importance that are financed from public funds. This poses a great challenge especially to civil infrastructure designers, as BIM planning requires specialist knowledge and appropriate software. At CGS Labs, we are developing new methods and approaches for 3D BIM modelling of road and railway corridors, which will result in software that will facilitate the time-consuming and complex work of designers. The paper describes the theoretical foundations and practical approach to BIM modelling for various characteristic types of projects. The development of these methods is supported by the knowledge and experience that the authors of the article have gained in their many years of work in the field of digitization of the built environment.

1 Introduction

In this paper, we discuss and compare four different practical approaches to BIM modelling of transport infrastructure. The basis for this was a single typical cross-section or expected final 3D/BIM model of the road section, which included a two-lane road with a bus stop.

The aim of the comparison was to quantitatively assess:

- The time component of each planning method,
- Comparison of calculated quantities for planning and construction, and last but not least,
- Comparison of the accuracy of the 3D/BIM model of the road.

The methods used to create the 3D road model project included:

- Standard method with defined sample lines and typical cross-sections,
- An advanced method of using defined typical cross-section profiles,
- The method used to produce surfaces,
- A hybrid method.

The standard method involves the traditional approach of building a 3D model of the road body between defined road cross-sections at defined (uniform or non-uniform) intervals between the sample lines along the road alignment. By using modern computer-aided design technologies in a CAD environment, this method provides a very fast and efficient way of processing and producing a 3D/BIM model of the road including the calculation of all material and element quantities required for construction or maintenance works and the corresponding attributed properties for further processing of the BIM models in other software solutions and for data exchange purposes.

Advanced 3D road modelling method basically follows the principle of traditional characteristic cross-section definition, but the 3D road modelling process is much more accurate, as it follows the 3D path of the road edges.

The direct surfacing method based on 3D road edges excludes the use of cross-sections. It relies on 3D road edge data obtained from the design centreline, level and cross-slope. Surfaces include both the top layers of the road body and the surfaces of individual layers (e.g. asphalt layers, roadbed, etc.).

The hybrid method combines the standard method in the area of the characteristic elements of the road body between the top layer and the bedding and the use of the surface method to define the area of the trench and embankment.

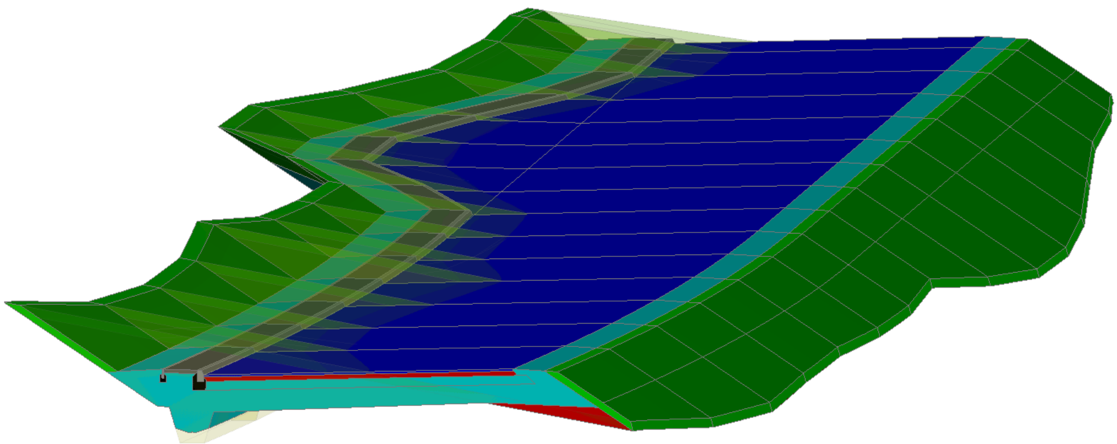

Figure 1: *3D/BIM model produced using the standard method including the necessary property data attached.*

2 Standard method for creating a 3D road model

The standard method of creating a road model comprises the design of the axle and the level, the calculation of superelevations, the determination of the reference sample lines along the axes, and finally the determination of the elements of the characteristic cross section, which is parametrically adjusted along the 3D designed road using modern technologies. A relatively accurate 3D model of the road body is then produced, including all individual layers and objects along the road alignment. By identifying the areas on each cross-section that belong to a particular road material or object, the required quantities of materials for embedment, excavation or embankment can be quickly calculated using a standard volume calculation method.

The standard 3D road model method can produce significantly more accurate results at user-identified locations for additional cross-sections or densification in areas of major round-offs, or in areas of significantly more rugged terrain or transitions between areas of cuttings and embankments.

The standard method for calculating volumes:

$$V = \frac{(A_1 + A_2)}{2} * d$$

where:

V - calculated volume/area [m2 /m3];
A1 - the value of the planimetric quantity in a profile [m1 /m2];
A2 - the value of the same planimetric quantity in the next profile [m1 /m2];
d – the distance between two adjacent profiles [m].

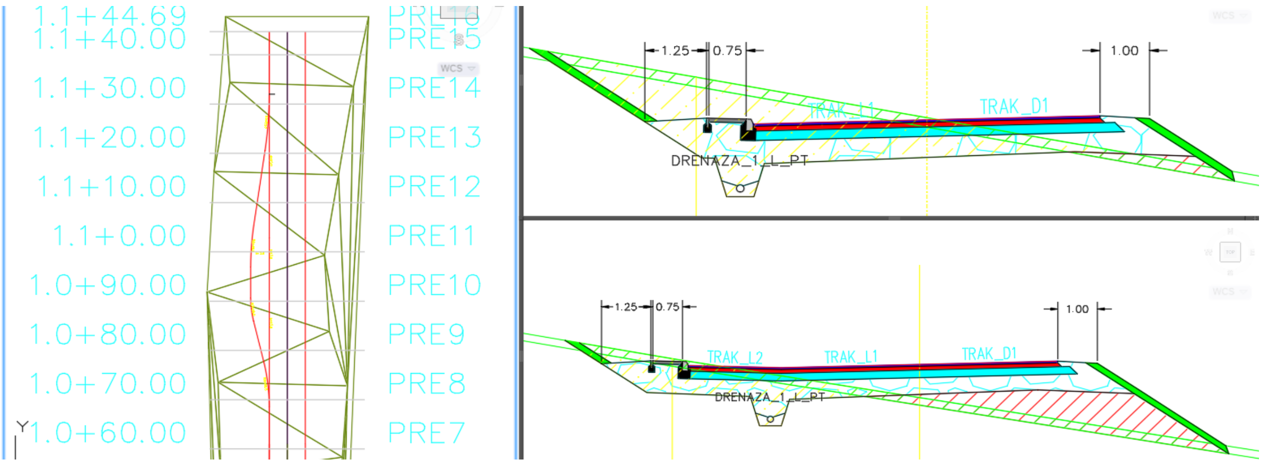

Figure 2: *Standard design of the planned road using characteristic cross-sections along the road axis.*

Table 1: *Calculated volumes in m3 using the modelling method by road profile.*

Cross sections interval	Fill	Cut	Pavement	AC11	AC22	AC33	TD	Humus	Humus removal
1 m	496,69	957,68	8,57	56,73	113,72	237,06	869,80	103,43	427,30
10 m	497,67	956,56	8,57	56,75	113,76	237,15	870,02	103,27	427,20
20 m	513,54	985,77	8,57	57,37	115,00	239,63	875,16	105,15	431,84

2.1 Advantages and disadvantages of the standard method

Advantages:

The standard method allows the fast and accurate design of a 3D road body on the "open" part of the road route, where there are no large variations in the defined geometry of the characteristic cross-section along the axes. It also allows very satisfactory design of additional elements of the 3D road body, such as the area of a bus stop, where the outer edges of the bus stop do not follow the curvature of the road axis.

It allows a very precise calculation of the quantities of materials and elements needed for the planned road section. By individually densifying the cross-sections at the necessary locations, the accuracy of the calculations can be increased considerably, while still keeping the number of cross-sections and the processing of the characteristic cross-sections sufficiently small.

The standard method allows the user to quickly and easily check the results, thanks to the established design process and the 2D/3D visual support at any point along the route of the designed road body.

Disadvantages:

The standard method has significant drawbacks in the area of major geometry changes at the outer edges of the road, whether road offsets or junctions, where the volume calculations and element geometry are based on the curvature of the design axis rather than the outer edge of the road.

The calculations of cut and fill volumes are less accurate, as the standard method does not consider the change in terrain between the cross-sections themselves.

There are also shortcomings in the production of an accurate 3D (solid) model of the road body in the areas of change of ditches and embankments along the road alignment, where significant densification of the sample lines is required for more accurate drawings and calculations of the 3D road models.

3 Road edge modelling method

The process of working with the road edge modelling method is initially very similar to the standard method. First, the terrain is inserted and processed, the centreline and the longitudinal profile are drawn and the superelevations are calculated. Based on this information, 3D edges are drawn, which are used as a starting point for the 3D model using the road edge modelling method, where the 3D axis along which the extension runs is defined as a new axis. As the 3D model building process follows the 3D road edge path, the final result is more accurate than the standard method.

Once the longitudinal profile has been created on the new axis, we proceed to define the section lines in the plan view, which are then inserted into the cross-sections. All remaining 3D edges and the road axis are defined as section lines. It is important to give them meaningful names so that later on we know exactly which 3D polyline is represented by each point in the cross-section.

Next, cross-sections are taken to create a 3D model. First, insert the terrain and the cross-section points. These are interconnected to give the top edge of the pavement structure. This is used to draw the upper and lower structure and the planum of the road. Other elements of the characteristic cross-section, such as kerbs, pedestrian crossings, cycle lanes, banks, banks, etc., are also drawn on each side.

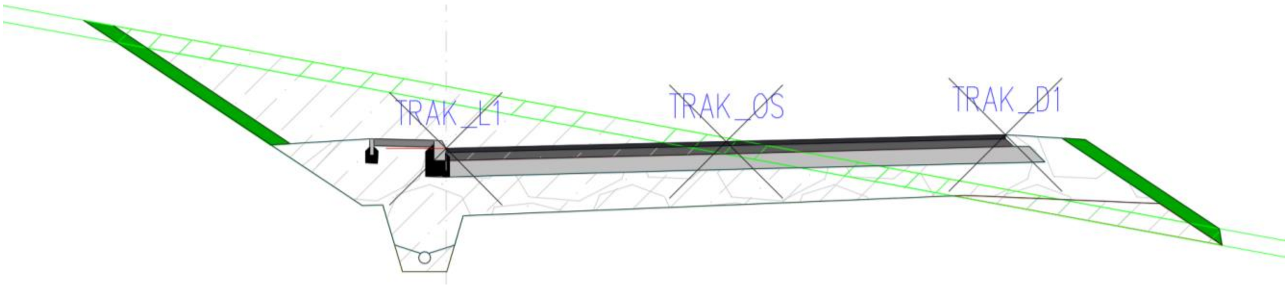

***Figure 3**: Designed cross-section for the road edge modelling method.*

In addition to the correct cross-sections, the correct choice of the method for calculating the volumes is also crucial for a correct final result. It is the engineer's task to critically assess the appropriateness of each calculation. Due to edge modelling, the centre of gravity of the planimetric volumes is no longer in the axis, so the Elling calculation method is chosen to calculate the volumes, where the volume is calculated using an approximation formula where the path of the centre of gravity is considered for the curved axis. (Massenberechnung aus Querprofilen (Elling), 1979) Due to the consideration of the position of the sample lines in space, the calculation is more accurate than the standard method. The values of the calculated quantities are shown in Table 2.

Elling calculating volumes method:

$$V = \frac{A_1 + A_2\sqrt{A_1 * A_2}}{3} * d$$

where:

V - calculated volume/area [m2 /m3];
A1 - the value of the planimetric quantity in a profile [m1 /m2];
A2 - the value of the same planimetric quantity in the next profile [m1 /m2];
d – the distance between the centres of gravity of the planimetric surfaces in two adjacent profiles [m].

Table 2: Calculated volumes in m3 using the road edge modelling method.

Cross sections interval	Fill	Cut	Pave-ment	AC11	AC22	AC33	TD	Humus	Humus re-moval
1 m	496,79	986,20	8,58	56,79	113,84	237,30	898,39	106,17	428,42
5 m	496,54	986,36	8,58	56,79	113,86	237,33	898,41	106,09	428,44
10 m	497,37	984,00	8,58	56,81	113,90	237,45	898,70	105,95	428,41

Due to the complexity of infrastructure projects, a combination of the standard method and the edge method is often used in practice. In this case, the edge method is used only in the area where there is an extension (an additional axis is created along the edge), while elsewhere the model is drawn based on the main axis. In this case, the cross-sections on the main axis are created as in the classical design, but when defining the TCS elements on the edges, additional cross-section points are reinserted to give the top edge of the roadway structure (as in the edge-by-edge method). In addition to modelling the extensions, the method is also used to create a 3D model of bus stops, service areas and classical and roundabout junctions.

3.1 Advantages and disadvantages of modelling on road edges

Advantages:

- Rapid and detailed production of a 3D model of the infrastructure along the entire route. The result is equally accurate whether the horizontal element is a bridge, a passageway or a circular arch.

- Simple, as it is similar to the standard method. The designer designs according to established procedures.
- More accurate production of 3D models in curves than the standard method. The standard method results in geometric changes in some elements in curves, e.g. curb width decreases/increases, while the perpendicular layout of the sample lines does not result in deviations when modelling along the edges of the roads.

Disadvantages:

- The method requires a little more work than the standard method, as a new axis and section lines have to be defined and then entered into the cross-sections.
- Greater attention should be paid to the correct choice of method for calculating volumes. If the Elling method is not chosen, there may be differences in the calculated volumes.

4 Surface creation method

With the surface modelling method, 3D modelling is performed in the layout or in the 3D space of a CAD platform. This method is intended to allow for more accurate and detailed modelling than modelling in a classical way (with sample lines and cross-sections). In this way, it is also possible to define the changes on the route between the cross-sections themselves and to show them in the 3D model. It is also possible to better adjust the linear elements that are linked to the digital terrain model, as this information is otherwise not captured between the cross-sections.

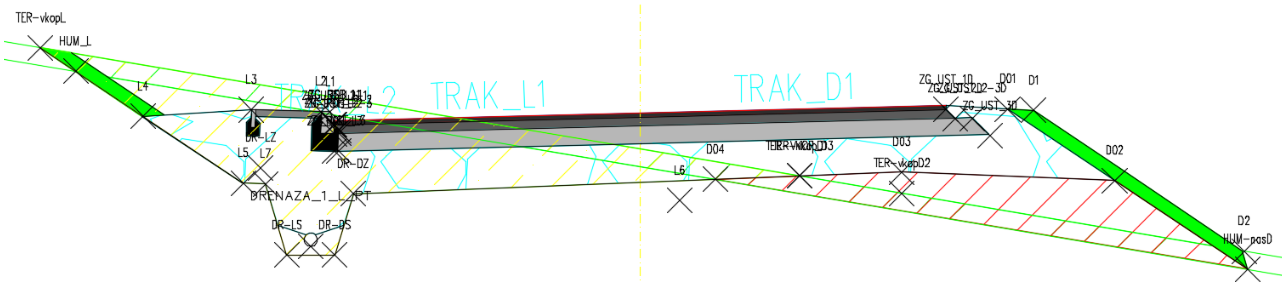

Figure 4: *Cross-section with defined limit points*

The source data in this case are 3D polylines, which were created on the basis of a given road level and superelevations. The 3D polylines of the road edges were, in this case, condensed to 10 cm to increase the accuracy of the model.

The software tool was used to define the lengths/heights/tilts/projections of the new lines according to the selected characteristic cross-section. This resulted in lines that are always perpendicular to the lines in the situation (unlike the classical approach where they are defined according to the position of the cross-sections), thus preserving the actual lengths of the individual elements between the profiles. All the boundary points of the layers and kerbs, as well as those of the embedment and embankments, have been defined in this way. The newly created 3D lines were used to produce the individual surfaces of the different layers of the pavement structure. The boundaries of the surfaces themselves must also be defined using this method. The surfaces were then used to calculate the necessary volumes for the entire route.

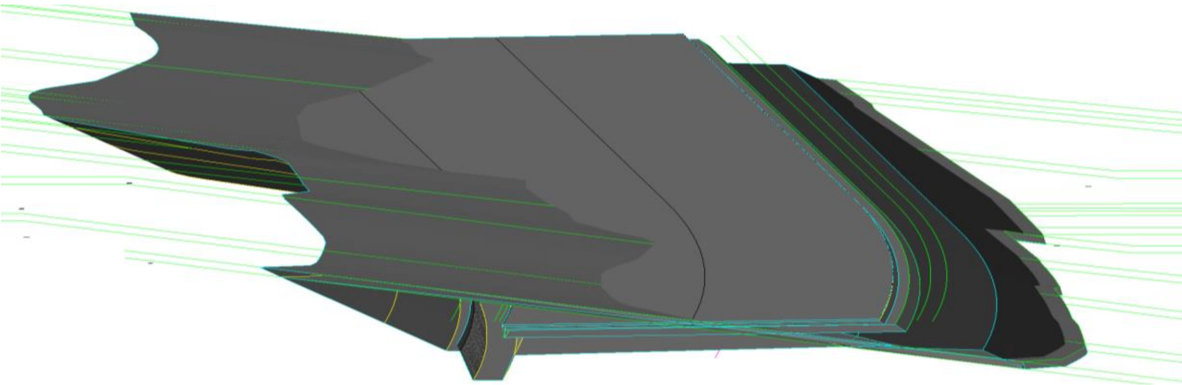

Figure 5: *Rendered surface areas of each layer by the surface area method*

Errors can occur due to a lack of precision of the source data. The densification of the 3D section lines and road edges also significantly changed the volumetric quantities in the case study. The number of vertices on the 3D line itself controls the number of triangles in the triangular mesh of the digital terrain model, and the volumes for excavations, embankments and other things can change. Other errors that can affect the accuracy of our quantities include poorly defined surface boundaries, lack of decimal precision in the construction of bank lines, etc.

Table 3: *Volumetric quantities in m3 by surface area method.*

Method	Cut	Fill	Pave-ment	AC11	AC22	AC33	TD	Humus	Humus removal
Surface	496,2	956,1	x	56,7	110,5	242,2	X	105,0	434,1

4.1 Advantages and disadvantages of the surface method

Advantages:

- A more accurate 3D model, as we can capture all the changes on the route, not just in the cross-section area.
- The ability to model in detail in a way that other 3D objects can be used.
- Possibility to include point objects in the model itself. Point objects can be excluded from the surface and not considered in the calculation of the different quantities.
- The lines that are tied to the terrain are more detailed, as they consider all spatial changes.

Disadvantages:

- For more complex cases, a large number of lines need to be produced, which is time-consuming.
- Additional work is involved in the production of individual surfaces and boundaries, which is not necessary with the standard method.
- The quantities are very dependent on the triangular mesh created, so we need to pay attention to the density of the 3D lines we use. Engineering judgement of the results is required.
- The creation of a classical 3D solid/solid model between surfaces is more difficult and requires additional tools, designers' skills and the additional provision of appropriate element property data.

5 Hybrid method

The hybrid model combines a standard modelling procedure with the use of banks and surfaces. The cross-sections are used to obtain the volumes of the roadway structure, while the banks are used to obtain the volumes of cuts, fills and humus. In the present case, the standard method with 10 m cross-sections and the surface method was used.

The aim of this approach is to design the roadway structure itself more quickly and, on the other hand, to increase the accuracy of the cut and fill volumes, as well as the accuracy of the 3D model of the embankments.

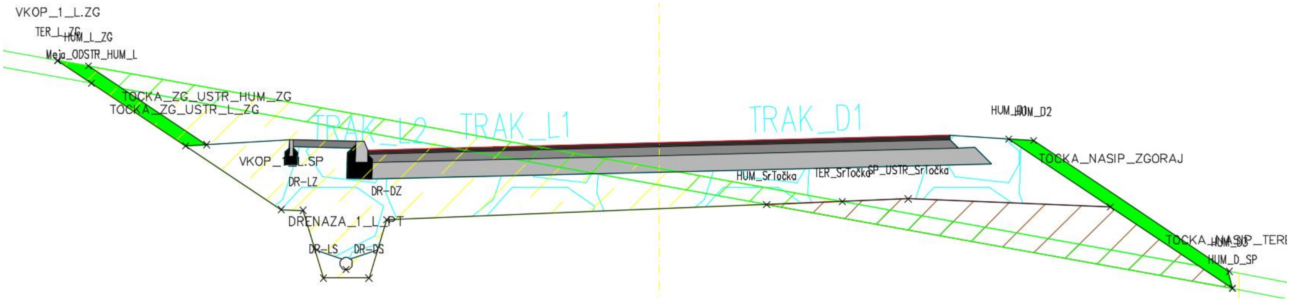

Figure 6: *Cross-section with defined intersection and boundary points*

The hybrid model process starts in a classical way with the drawing of the axes and placing of the sample lines. Then the longitudinal section is drawn, profile line defined and superelevations calculated. The cross-sections are then used to define the intersection points at the boundaries of the pavement structure. These points can be used to create 3D cross-section lines in the situation to which the new lines or banks are tied.

The volumes for the roadway structure are derived from the planimetric quantities of the cross-sections, distances between them and the calculation method used. For embankments, the upper and lower surfaces of the trenches, embankments and humus layer need to be created. The boundary for each surface is also created and then the volume between each surface in the situation can be calculated.

The errors are similar to the surface method. Care must be taken to ensure that both the edges of the road and the rest of the 3D section lines used to create the surfaces are sufficiently condensed. However, an error in the pavement layers may occur due to a combination of geometric changes and too few cross-sections.

Table 4: *Calculated volumes in m3 using the road edge modelling method.*

Method	Cut	Fill	Pave-ment	AC11	AC22	AC33	TD	Humus	Humus removal
HYBRID 10 m + Surfaces	489,0	958,8	8,6	56,7	113,8	237,1	870,0	105,3	427,9

5.1 Advantages and disadvantages of the hybrid method

Advantages:

- More accurate 3D model and cut/fill quantities than the standard method, as changes in terrain between profiles are also considered.
- Faster pavement construction than the surface method, as fewer lines and surfaces are required.

Disadvantages:

- The knowledge needed to apply the different methods and evaluate the results.
- Accuracy depends on several factors, as two different methods are used.

6 Conclusion

This paper presents and compares four different 3D BIM modelling methods for road and rail infrastructure. The starting point was provided by an identically defined characteristic cross-section along a dual roadway with a bus stop. Based on the same input data, it was then possible to compare the 3D models and the calculated volumes according to the method used. The resulting values are shown in Tables 5 and 6.

***Table 5**: Calculated volumes in m3 according to the modelling method used.*

Method	Cut	Fill	Pave-ment	AC11	AC22	AC33	TD	Humus	Humus removal
STANDARD Interval 10 m	497,7	956,6	8,6	56,7	113,8	237,1	870,0	103,3	427,2
ROAD EDGES Interval 10 m	497,4	984,0	8,6	56,8	113,9	237,5	898,7	106,0	428,4
SURFACE	496,2	956,1	x	56,7	110,5	242,2	X	105,0	434,1
HYBRID 10 m + Surfaces	489,0	958,8	8,6	56,7	113,8	237,1	870,0	105,3	427,9

***Table 6:** The difference in volumes according to the modelling method used.*

	Cut	Fill	Pave-ment	AC11	AC22	AC33	TD	Humus	Humus removal
Max. [m3]	497,7	984,0	8,6	56,8	113,9	242,2	898,7	106,0	434,1
Min. [m3]	489,0	956,1	8,6	56,7	110,5	237,1	870,0	103,3	427,2
The difference [m3]	8,7	27,9	0,0	0,1	3,4	5,1	28,7	2,7	6,9
The difference [%]	1,75	2,84	0,16	0,21	2,97	2,09	3,19	2,53	1,58

We found that the 3D models and their quantity values are not significantly different from each other, as initially expected. Even when increasing or decreasing the distance between the sample lines, we obtained very similar results. Therefore, we cannot directly assess which of the methods gives better results in the production of 3D/BIM models or in the calculation of quantities. However, based on the advantages and disadvantages, the designer can critically decide in which cases to choose one of the described methods.

We have also found that the standard method is the fastest, as the designer models according to established procedures and has no extra work to do. The biggest difference was in the 3D excavation model itself, where the difference in excavation volume between the most accurate and the standard method was still less than 3%. It took much more time to build the model using the surface method. This is quite demanding for the user as it does not have specially adapted tools.

In future studies, we aim to produce more models from real construction projects, where the values obtained from the 3D models can also be compared with the contractor's invoiced quantities. In this way, we could better assess which of the 3D/BIM modelling methods gives the best results. In addition, the differences in quantities between the different types and complexities of terrain are defined in the road design guidelines.

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