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A novel approach towards automated derivation of two-dimensional numerical models from geotechnical building information models (BIM)

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ABSTRACT: This paper presents an approach towards deriving robust, two-dimensional numerical models from geotechnical building information models to support automated and integrated workflows. The proposed approach addressing identified difficulties in deriving 2D numerical models from geotechnical BIM-Models of higher dimensions is based on multiple stages of geometry processing whilst considering linked alphanumeric, relational and geometric information. Objects are filtered and grouped using their classification. For a selection of classes knowledge-based modelling and idealization rules are applied. A section through the soil elements is created. The returned geometry is simplified and processed striving towards optimal meshing capabilities whilst maintaining geological and geometrical coherency. The processed and structured geometry with its linked data and additional knowledge-based modelling rules is used to generate the numerical model, including its calculation procedure. Finally, calculation results can be transferred back to the BIM-model. The process is implemented using common modelling and simulation tools. It is shown that calculation-ready 2D-FEM models can be derived.

Keywords: Finite Element Method; Building Information Modelling; BIM-to-FEM; Geometry simplification

1 INTRODUCTION

1.1 BIM-to-FEM in geotechnics

With increasing usage of Building Information Modelling (BIM) in planning processes, the availability of digital subsurface models is growing. The geotechnical BIM models contain geometrical information on subsoil and geotechnical structures. Additionally, they contain non-geometrical data, for example property and relationship descriptions.

Numerical calculations, often using the Finite Element Method (FEM), are an integral element in the geotechnical design practice. The computational models are either two or three dimensional and are currently mainly manually generated. The numerical models also contain geometrical and non-geometrical data describing the geotechnical system. The information already contained in the BIM is partially remodelled. Approaches exist to minimise the remodelling and to use the information from the BIM model by integrating these technologies (BIM-to-FEM).

Ninić et al. (2021), Ninić et al. (2020) and Alsahly et al. (2020) propose an integrated workflow for tunnel design analysis, in which 3D-geometries are transferred to the numerical model by exporting the geometry as non-uniform rational basis spline (NURBS) surfaces and the non-geometric information is passed as a separate text file. Calculation results are returned and can be viewed

in the BIM authoring software. Huang et al. (2022) present a BIM-to-FEM integration for tunnels as well. Klinc et al. (2021) and Fabozzi et al. (2021) use similar, less holistic and automated approaches, using .dwg-files for geometry transfer. Li et al. (2022) apply a 3D BIM-to-FEM method for underground powerhouse caverns. Xie et al. (2022) present a 3D BIM-to-FEM integration for an excavation pit, in which they separate solid (soil) and structural elements before transferring their geometries to the analysis software. They point out, that excavation steps need to be considered in the mesh generation process.

Obergrießer et al. (2011) use a parametric model in which a roadway with embankments and cuttings is described by parametric sections along a path. 2D sections are derived from this model. The integration with the calculation software uses .xml-files and is bidirectional. Hendriks (2018) creates sections of an excavation pit model with *OpenGL* and calculates them using *PLAXIS 2D*. Bailie et al. (2020) automate parts of the BIM-to-FEM process by extracting section geometries from the BIM model using *Rhino* and *Grasshopper* and writing it to a .csv-file, which is used to create geometries in *PLAXIS 2D*.

The current, common practice for deriving a 2D numerical model from BIM model is to create a 2D section in the BIM authoring software, trim the section, export the section geometry in CAD-format and finally import

the files into the numerical software, as shown in van der Sloot (2022). The BIM modelling software used allows for simplification of line geometries by setting a minimum allowable distance between nodes of the exported polylines, see Seequent Limited (2020).

Current geotechnical BIM-to-FEM research focuses on 3D numerical models, while the need for 2D geotechnical models is seen. Most of the aforementioned publications point out, that a lot of manual adjustment of geometries and alphanumeric information is required, even though simple subsoil geometries are considered.

1.2 Challenges and goals

The aim of the proposed method is to enable automated design analysis of a geotechnical structure using a 2D-numerical model, here FEM, based on its BIM representation. The method needs to be able to handle complex boundary conditions and geometries, while being able to generate reasonable meshes for calculation. The focus of this work lies on the process and methodology rather than geometry / mesh optimisation.

2 CONCEPTUAL LAYOUT

BIM-models, which are used as the starting point, contain hierarchical, structured data and information according to a certain, pre-defined schema. To obtain a two-dimensional model, a section cut is made through the three-dimensional geometry. The link between 2D geometry and the information of its 3D equivalent is maintained. The next step is to apply modelling and mapping rules that use the above information, hardcoded expert knowledge and general knowledge to generate the model for numerical calculations. The resulting model and the decisions that led to it are documented. The relationships between the elements in the numerical model and the BIM model are tracked so that information from the numerical modelling tool can be mapped to the BIM model.

A core concept of the implementation shown is that it is known from the problem description, which information is needed to create the corresponding numerical model using a case-based system. Based on this, the BIM model is queried and the results are reasoned. This allows complete numerical models to be derived from incomplete or inconsistent BIM models, e.g. by using rule-based reasoning.

The geometry received from the section cut operation is not passed directly to the meshing tool. Due to the complex and detailed geometries of the BIM models, artefacts as well as thin or pointed shapes may be obtained from the section cut operation. These can result in distorted mesh elements, inhomogeneous mesh element sizes, or affect meshing capabilities during the meshing process. In the proposed process, the geometry

is re-parametrized, adjusted and/or simplified taking into account the geological topology, target mesh parameters as well as allowed deviations from the BIM geometry to ensure a high mesh quality.

3 IMPLEMENTATION

3.1 Used software

The subsoil model is created using *Leapfrog Works* (Seequent). The geotechnical structure is modelled in *Revit* (Autodesk, version 2023.1.1). By running *Rhino.Inside.Revit*, it is possible to interact between *Revit* and *Rhinoceros 3D* (Robert McNeel & Associates, *Rhino*, version 7.17) and its visual scripting tool *Grasshopper*, which are used for scripting and geometry manipulation. A connection to a *Flask* web server is established using the *Grasshopper* plugin *Hops*, which is used to communicate with the 2D-FEM software *PLAXIS 2D* (Bentley, *PLAXIS*, version 22.00) through its Remote Scripting Interface.

The described setup allows for asynchronous execution and running the BIM and FEM applications on different machines. The established live link between visual scripting tool and the finite element software with the developed components allows algorithmic modelling for the FEM-software. As the following implementation aims at a high degree of automation with decision making, the *Grasshopper* definition mainly consists of scripting components and *Hops* components. The scripting components interact with *Revit's* and *Rhino's* APIs, external data sources, geometry and data processing. *Hops* components are used to interact with the *Flask* server.

3.2 Case study

A case study is carried out to empirically evaluate the feasibility and effectiveness of the framework and concept. Both the excavation pit and subsoil model are slightly adapted from real projects in the northern part of Germany. Figure 1 **Error! Reference source not found.** shows the considered rectangular excavation pit by means of a single supported sheet pile wall. The wall depth is 12 m and the struts are located 1 m below the ground surface. The pit is excavated in three steps. Excavations are represented by void volumes, which are subtracted (Boolean difference) from the subsoil volumes.

The soil stratification is highly inhomogeneous and contains multiple lenses. The subsoil model, shown in Figure 2, consists of 90 closed, triangular surface meshes with a total of 1.259.400 vertices forming 419.800 faces. The dimensions are approximately 350 m x 750 m x 70 m. The construction sequence is represented by an external Gantt chart, which is linked to the elements of the BIM model.



Figure 1 BIM model of the sheet pile wall

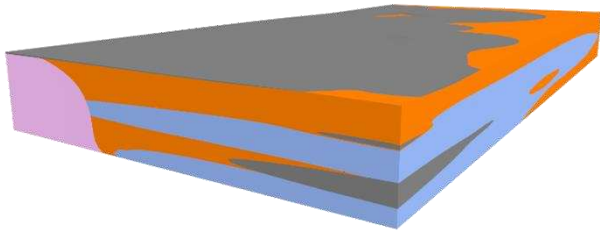


Figure 2 BIM model subsoil, created with Leapfrog Works

3.3 Filtering elements and mapping materials

BIM models contain plentiful information that is irrelevant for the numerical simulation of geotechnical problems. To determine the relevant information, the problem description (here: deflection analysis of an excavation pit) is required, which can be done manually or automatically using a reasoning algorithm that evaluates model content and user input on areas of interest, if available. The knowledge base is then searched for the information needed for the case. Leveraging the underlying ontology and data structures, the corresponding elements of the BIM models can be filtered. Entities of different classes, e.g. soil elements, struts, sheet piling elements, external loads, are handled separately.

Each object with a physical representation in the numerical model has a material assigned to it, while multiple elements may have the same material assigned to them. The parameters used to describe materials differ between the BIM and the FEM domains, such that a direct mapping is usually not possible, unless the BIM model is specifically prepared for this use case. Therefore, the properties of the material associated with an element in the BIM model are queried first, followed by the properties of the element itself. Depending on how the materials are described in the numerical software, geometrical information is required. For example, cross-sectional areas are required for stiffness calculation of plate materials and spacings are required to define anchor and embedded beam materials. The geometric attributes can be derived from the BIM model with little effort, even if several elements outside the section have to be queried.

If the material data in the numerical software is not yet complete, look-up tables, correlations or default values can be used via a set of rules that use information gained from the BIM models to query the database, where general knowledge is stored. This ensures the completeness of the numerical model. For example, if the BIM model only contains the name and a very schematic geometric representation of a sheet pile wall, the name can be used to look up cross-sectional areas, moments of inertia etc. in a product information table.

3.4 Geometry processing

BIM models typically have a significantly higher level of detail in geometry representation than numerical models. Small geometrical features lead to increased computation times, while complex models can often lead to ill-conditioned matrices that produce inaccurate results. These problems can be addressed by using geometry simplification, idealisation and reduction techniques. When building a numerical model, the geotechnical expert performs these steps manually using his or her knowledge, e.g. deciding what features are relevant to the calculation, how real-world objects are modelled in the numerical domain, and what geometries can be reasonably meshed.

Thakur et al. (2009) provide an overview of different techniques for simplifying CAD geometries for physics-based simulations. Prabhakar and Sheppard (1994) propose a knowledge-based approach to model idealisation using a rule-based expert system. The automated approaches presented by the authors mainly address problems in mechanical engineering. Jia et al. (2022) propose an ontology-based BIM-to-FEM approach where the element and mesh type are reasoned by a decision-making system with component type, size and function as inputs. These concepts are reflected in the implementation presented here.

In the herein proposed approach, the geometry handling follows the described process of filtering relevant model elements based on the identified case. Modelling rules define, which types of objects are represented by 1-dimensional elements and which are represented by 2-dimensional elements in the numerical model. In the case study, the objects, that are transferred are sheet pile walls, struts and soil elements.

3.4.1 1-dimensional elements

Struts and sheet piles are treated in a similar way, as both are represented by 1-dimensional elements in the 2D numerical domain. When an element of a particular type is identified, it is looked up in the modelling rules, how the element is represented in the numerical model. In the case of the sheet pile wall, it is represented by a beam element wrapped by interface elements in FEM model. Beam element geometry is described by a line, which in turn is defined by its start and end point. These

geometric features are extracted from the BIM-model and transferred. The chosen geometry extraction process for sheet piling computes an object-orientated bounding box to determine the centreline, which allows inclined sheet piling to be considered. An additional modelling rule is that interface elements on sheet pile walls follow the beam's geometry on both sides, but extend 0.5 m beyond the depth of the beam end point in order to avoid the singularity point. As interface elements are modelled using a line geometry as a host and that such geometry is not yet present in the model, it is added.

3.4.2 2-dimensional elements

Soil geometries are represented in the chosen FEM application as 2D continuum elements. These can be created by defining boreholes and then letting the software automatically connect areas of the same soil type linearly, or by explicitly defining soil polygons. The second method is more flexible and therefore more suitable for BIM-to-FEM applications. Unlike other tools, the used FEM software does not allow for non-uniform rational basis splines (NURBS) as an input for its pre-processing. Each vertex of a polygon used as a geometric input is also a vertex of the automatically generated triangular mesh of finite elements. Another limitation is, that it is not possible to directly model a surface with a hole. Instead, the larger polygon should be modelled first and then the smaller polygon must be subtracted to avoid additional constraint points. As a result, the limitations of the chosen software applications influence how the two-dimensional geometry is created, transferred and therefore simplified / optimised.

Consequently, geometry processing for soil elements is done considering reduction or elimination of transferred polygons that force low mesh quality. Subsequently, it is described, how the geometry is handled in this proposal, and then elaborated, which potential issues may be addressed by doing so.

The starting point is a collection of 3D mesh geometries obtained from the BIM model. Mesh repair operations are applied in a pre-processing step to ensure these geometries are closed. Each 3D mesh is intersected with the section plane, returning points which are connected to closed polylines. Vertices, that are within a small tolerance distance, are processed in a way, that visually overlapping polyline segments are actually defined by the same points. For ease of use, it is recommended to translate and rotate the received elements such, that the top point of the retaining wall is at (0|0|0) and that all lines are in the xz-plane.

The FE model area is computed following a set of modelling rules. For a retaining wall system, the model area is rectangular and its size is determined by following the recommendations in DGGT (2014), considering excavation depths, pit width and anchor lengths as well

as angles obtained from the BIM model. All soil contours are intersected with the model area boundary. The parts within the rectangle are preserved. Where the model area boundaries split a closed polyline into multiple closed polylines, a separate soil element is created for each resulting polyline. This is dictated by the concept that each soil element is geometrically described by its outer boundary curves. Geometric modification operations are only applied to these boundary curves or to parts of them. The model area boundaries are also used to check, if the BIM model is sufficiently extensive. There are numerous ways to address the issue of too small BIM models, such as extrapolation or checking for the influence of closer model boundaries by means of verification calculations. Here, additional vertices with the values with xy-coordinates from the model area boundaries and z-coordinates from the vertices closest to the model boundary are added.

Excavation geometries are extracted from the BIM-model and intersected with the named cut plane. The soil geometries are split so soil elements that belong to an excavation step are separated.

A soil element hierarchy is derived from the BIM model, which can be used to reason about geological processes in future research. In addition to querying chronosequence information, the topology of the section is evaluated by creating an adjacency matrix of all soil polygons using the ratio of common perimeter length to total perimeter length of the element as weights. Figure 33 shows an example section with its adjacency matrix. Row "0" is read as: Soil element 0 shares 100% of its perimeter curves with itself, 0% with soil elements 1, 2, 3, 5, 51% with soil element 4 and 49% with soil element 6. The values of the row add up to 200%, if all perimeter curves are shared with other soil elements. Therefore, it has no contact with model boundaries, but is enclosed by the number of elements, which values are not equal to 0 and part of the main diagonal.

Lenses are identified and classified using the adjacency matrix in conjunction with queries on properties and area calculations. For example, soil element 3 is completely encapsulated by soil element 6 and has a small area, therefore it is considered to be a lens. If it is senseful to remove this lens, which is evaluated by size and internal angles considering the desired mesh element size, it is dropped along with its congruent correspondence of soil type 6. If a lens encapsulated by two layers is to be removed, a curve is fitted in between the two common points of the three elements, as shown in Figure b) and c). It replaces the segments of the encapsulating soil elements, which are also part of the vertices of the lens to be removed. For the removal of a lens with three encapsulating soil elements, the intersection point of the three joined lines can be used to rebuild the geometry. The soil adjacency matrix is recomputed after each geometry modification.

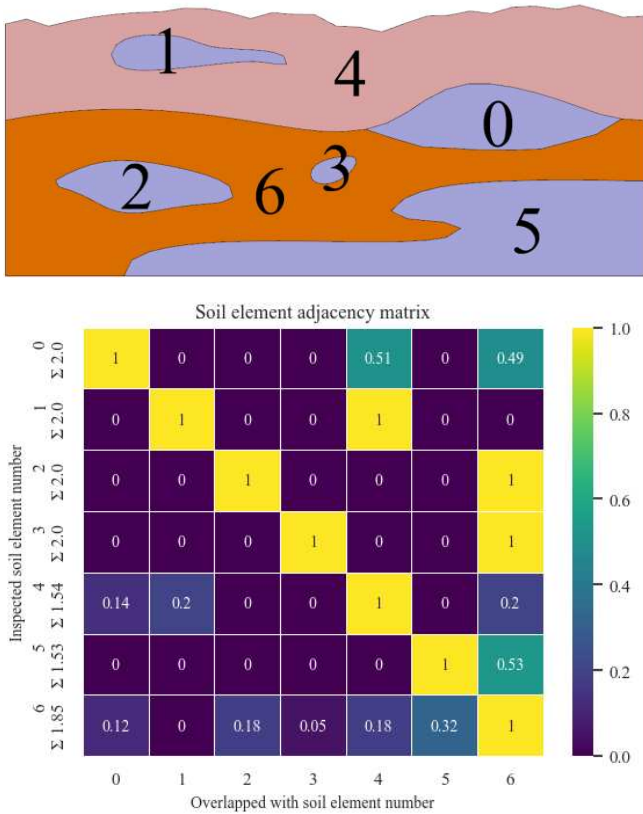


Figure 3 Soil section with corresponding adjacency matrix

The remaining geometries are simplified in a way that preserves the initial topology. Therefore, the boundaries of each soil element are split into multiple curves, using vertical sections and points shared with two other elements for splitting. An adjacency is calculated for those lines. As a result, the model area is then described by an ordered collection of parametric curves

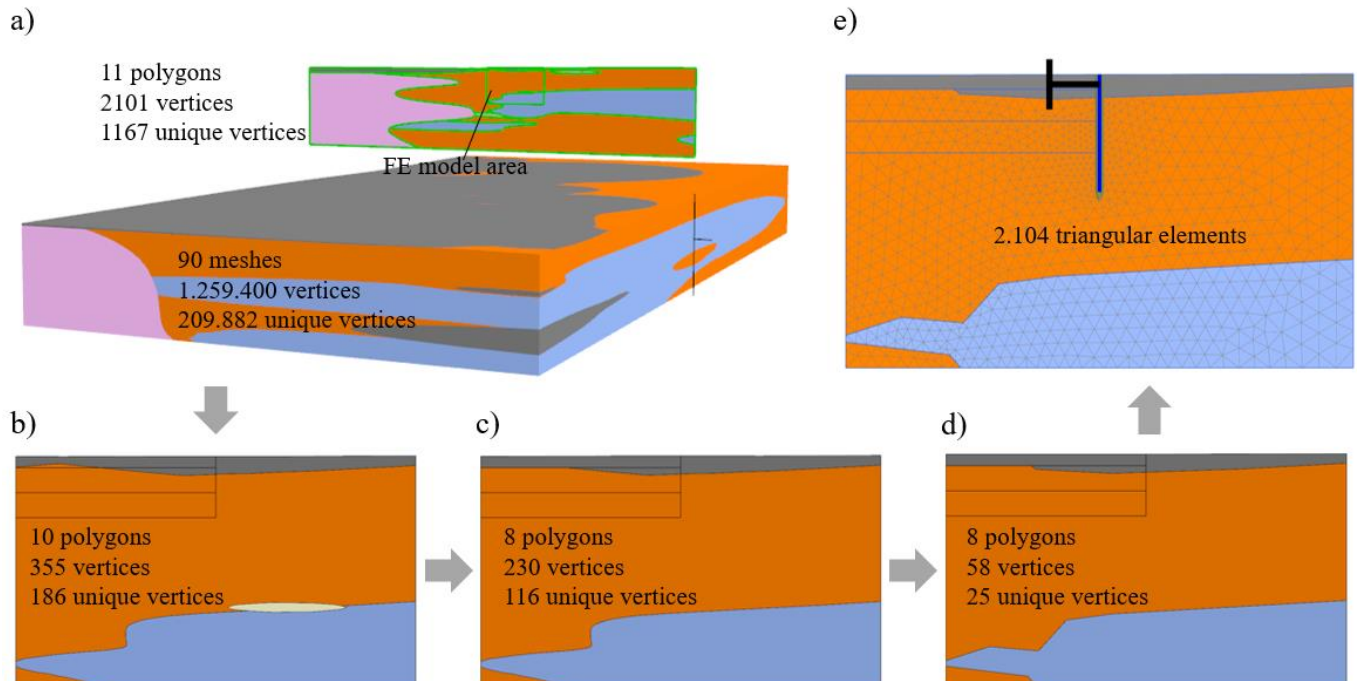


Figure 4 Process of handling soil geometries

and an overarching topology that can now be used for further simplifications and optimisations. Figure c) and d) shows an exemplary, basic simplification, where the lines with a high number of vertices are simplified by fitting a NURBS curve which is then approximated by a polyline. All polylines are simplified using the Douglas-Peucker-algorithm, see Douglas and Peucker (1973). Finally, vertices forming a sharp angle in a polygon and are not part of the model boundaries or an excavation line are allowed to move towards the sharp corner. The remaining vertices of the curve are proportionally moved using the curve domain. If a modified curve is part of several soil elements, as it can be derived from the adjacency matrix, the corresponding curves are also updated such that no gaps occur.

Finally, the polygons are transferred to the used finite element software, materials are assigned and the geometry is meshed, see Figure d) and e). The mesh element quality is between 0.4 and 1, using the ratio of the diameters of the inner and outer circles normalized to an equilateral triangle as quality metric. As the link between the BIM objects and those in the numerical domain is maintained throughout the entire process, mesh geometries, calculation results etc. can be transferred back to the BIM model and documented.

3.5 Additional information processing

Additional modelling rules are used to map the missing information. The procedure is like the one described for material mapping. For example, staged construction phases are created based on the external time schedule. If an element is not linked there, its phases in the BIM model are considered. If the element is an excavation instance, a reasoning for usual construction sequences

is conducted. External loads are also added to the numerical model, using the dimension reduction approach described in Beck (2022).

4 DISCUSSION AND CONCLUSIONS

The proposed method enables automated derivation of 2D numerical models from BIM models using a knowledge-based approach. Simplifications are made using a topology-driven approach and can automatically be visualized, documented and quantified.

The implementation is carried out using software solutions commonly used in geotechnical practice emphasizing practical applicability. A live connection has been established between *Grasshopper*, *Rhino*, *Revit* and *PLAXIS*. The process is automated so that no human interaction is necessary. However, it is possible to interact with the transfer process by editing parameters in the BIM models, the knowledge base or at specific points in the modelling rules.

Further standardization and generalization can add value especially when the BIM modeller and the FE modeller are different. Future work will extend the method to additional geotechnical problems as well as test and validate it on additional projects. The developed pipeline for deriving the parametric model can be used as a basis for geometry-based mesh optimisations.

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