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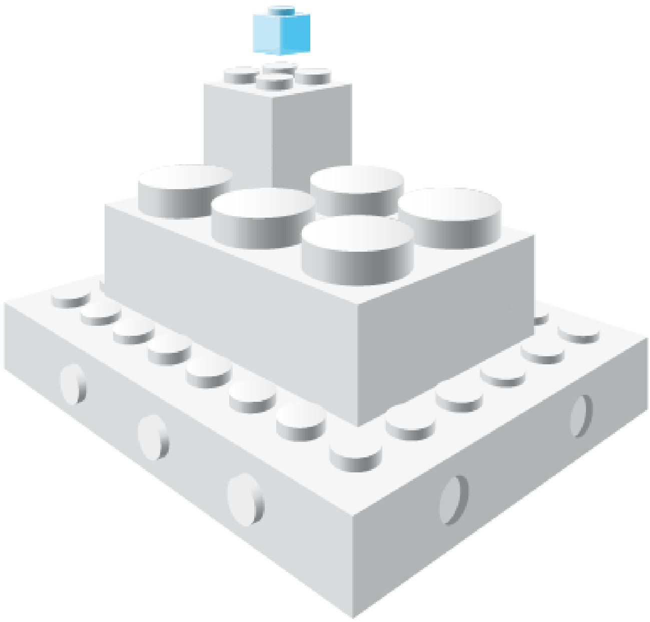

CHGEOL
Schweizer Geologen Verband
Association suisse des géologues
Associazione svizzera dei geologi
Associaziun svizra dals geologs
Swiss Association of Geologists

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Fachhochschule Nordwestschweiz
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Imprint

Innosuisse project partners
Project management: Swiss Association of Geologists CHGEOL
Implementation partner: Swiss Geological Survey swisstopo
Research partner: Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW

Project control
Johannes Graf, Swiss Association of Geologists CHGEOL
Andreas Möri, Swiss Geological Survey swisstopo
Manfred Huber, Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW

Project management
Michael Köbberich, Swiss Association of Geologists CHGEOL
Oliver Schneider, Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW

Advisory group
Andri Largiadèr, Forestry and Natural Hazards Office, Graubünden
Matthias Folly, Federal Roads Office FEDRO
Daniel Figi, Büro für Technische Geologie BTG
Philippe Schwab, De Cérenville Géotechnique SA
Hans-Rudolf Graf, Dr. von Moos AG
Matthias Preisig, GeoMod ingénieurs conseils SA
Franz Schenker, Geologik AG
Daniel Tobler, GEOTEST AG
Martin Stolz, Geotechnik Schweiz
Pierre Gander, Jäckli Geologie AG
Adrian Auckenthaler, Conference Geological Subsurface
Manfred Thüring, Lombardi Group GmbH
Severin Wälchli, National Cooperative for the Disposal of Radioactive Waste NAGRA
Michael Stockmeyer, Swiss Federal Railways SBB
Benno Staub, Vereinigung Kantonaler Feuerversicherungen VKF

Core team
Michael Köbberich, Swiss Association of Geologists CHGEOL
Stefan Volken, Swiss Geological Survey swisstopo
Philip Wehrens, Swiss Geological Survey swisstopo
Oliver Schneider, Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW
Lukas Schildknecht, Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW
Thomas Gafner, Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW

Authors
Michael Köbberich, Oliver Schneider, Lukas Schildknecht, Thomas Gafner, Stefan Volken, Philip Wehrens, Matthias Preisig, Philippe Schwab, Benno Staub, Reto Grischott, Daniel Figi, Stefanie Wirth, René Löpfe, Simon Roth, Manfred Thüring, Michael Stockmeyer, Johannes Graf, Manfred Huber, Andreas Möri.

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Contact
Michael Köbberich: michael.koebberich@chgeol.ch

Abstract

There are hardly any major projects today in structural or infrastructure engineering for which cross-disciplinary collaboration using digital methods is not of essential importance. These new forms of collaboration do not stop at geology and raise fundamental questions about the digital continuity of information. Geologists are valued experts in planning and construction processes, whose expertise should be efficiently and effectively integrated into the overall project to ensure the quality and safety of our civil works in the future.

GEOL_BIM addresses the question of the integration of geology into the increasingly digital forms of collaboration. The focus of attention is on interoperability and the digital continuity of geological information. Using three application areas as examples, GEOL_BIM examines the requirements for exchanging information pertaining to the topics of tunnelling, subsoil and natural hazards. In the case of natural hazards, the focus was on permanent ground movements. Commonalities were identified across the topics with regard to the information requirements for cooperation in the application areas investigated. For the case studies investigated, the necessary geological information and its interrelationships can be described with a conceptual data model. GEOL_BIM relies on the two data exchange models of the Geoscience Markup Language (GeoSciML) and the Industry Foundation Classes (IFC), which are used worldwide today, which ensures the international compatibility of the solution proposal developed. The innovation project thereby ventures a first step towards an industry-wide harmonised exchange of geological information for cooperation in civil engineering.

To keep the entry barrier to the results of GEOL_BIM as low as possible, the proposed solution consists of an easily accessible web application that does not require any programming knowledge. This application enables the transfer of structured borehole information, geological units and voxel models with the help of tools developed in the Python programming language, which are just as open and freely available as the web application itself. The structure of the geological information is based on the conceptual data model derived from the case studies investigated. The data models developed will become the responsibility of the Swiss Geological Survey swisstopo once the project is completed, where they will be maintained and, if necessary, further developed together with interested specialist groups. After completion of the innovation project, based on a further education and training concept, it should be shown how access to the jointly developed findings could be maintained in the future.

The Swiss Geological Survey swisstopo and the Institute of Digital Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW, under the direction of the Swiss Association of Geologists CHGEOL, are responsible for the development of this proposed solution for the GEOL_BIM Project, which is co-financed by the Swiss Innovation Agency Innosuisse. The project has broad support from the private sector as well as from authorities and associations.

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1.1 Introduction

1.1.1 Geology and BIM

Geological information is an essential basis for many planning, construction as well as operational aspects of civil works. This information must be combined with the information from the other disciplines involved in the task. The availability of integrated information from different technical fields is an essential prerequisite for good interdisciplinary cooperation in planning and construction projects as well as during the operational phase of man-made structures.
With the rapidly advancing digitalisation of planning and construction processes in the context of Building Information Modelling (BIM), structured and machine-readable information increasingly supports data-based decision-making. In a networked world, much of the geological information still contained in plans, sections and reports today, could in the future be exchanged in a harmonised and structured form. For collaboration in construction projects, geologists are therefore also increasingly relying on digital construction models to communicate their own technical expertise. This does not necessarily require an adaptation of the subject-specific, geological working method, but it does require an adaptation of the processing, storage and provision of the geological results.
The benefits from the application of the BIM method for geology can occur on two levels. On the one hand, the application of the BIM method promotes better professional cooperation with other disciplines involved in the man-made structure. With BIM, geological information can be integrated more directly into the pool of other building information, thus creating the basis for better understanding, discussion and solution finding. On the other hand, geologists not only benefit from harmonised and standardised information in the construction process, but a common language basis also supports professional communication within the discipline of geology.

1.1.2 Challenges

The development and introduction of a (uniform) data model for geology is challenging. Very different, sometimes very detailed information is required to deal with the various geological issues. There are various national and international data models for geology, each with a different technical focus. An established and comprehensive geological data model is an urgent necessity for BIM and the digitalisation of geology in general.
Compared to building models in the narrower sense, geological models have additional specifications that need to be considered when developing and implementing a data model. These include potentially large spatial extents with consequences for the amount of data needed to represent the geometric bodies, the consideration of distortions and the use of geodetic coordinate systems. In addition to the aspects mentioned, the type of analysis and the evaluation of geological information sometimes require special functions for the visual representation in viewers, which are rarely available in the products commonly used in the BIM environment today.
Another discipline-specific challenge with geological information is dealing with uncertainties. It is in the nature of things that there is uncertainty in a lot of geological information. It must be possible to represent the amount of an uncertainty and, if necessary, also the spatial extent of the uncertainty of an item together with the actual item's information itself.

1.1.3 GEOL_BIM and the accessibility of the results

The Swiss Association of Geologists CHGEOL launched and executed the GEOL_BIM project together with the Swiss Geological Survey of the Federal Office of Topography swisstopo and the research partner Institute of Digital Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW. The project received technical and financial support from 15 renowned authorities, organisations and private-sector companies. In addition, the Swiss Innovation Agency Innosuisse provided financial support for GEOL_BIM.

Within this framework, basic principles and tools for the linking and integration of geological information into the BIM-based working method of planning and construction projects were developed. On the one hand, the aim of the project is to develop a data model with which geological information can be mapped in a uniformly structured way. In doing so, the specifically Swiss concerns should be aligned with established international standards as far as possible (compatibility). On the other hand, on the basis of the data model, specific paths are to be shown and tools developed with which geological information can be integrated into digital building models via the open BIM standard IFC (Industry Foundation Classes) and analysed with BIM tools. The developed solutions were exemplarily applied and validated in five specific use cases.

The solutions developed are publicly and freely accessible, so that the knowledge gained can be used freely throughout the industry. This includes detailed documentation on theoretical aspects and the data models as well as the source code of the implemented adapters and applications. In addition, a web application for transforming geological information to IFC is freely available to interested parties for at least two years beyond the end of the project. As part of the project, the first proposal for a training and further education concept was also developed. Based on this concept, it will be evaluated in the follow-up to the project, how the knowledge gained can be passed on to experts.

1.2 Solution concepts and results

1.2.1 GEOL_BIM data models

In a basic research and analysis, various national and international data models are identified and their technical domain and suitability for the objectives of GEOL_BIM are assessed (including AGS, AGSi, INSPIRE GE, LandInfra, swisstopo data models). The decision was taken to use the OGC data model Geoscience Markup Language (GeoSciML) as the GEOL_BIM reference model. GeoSciML is defined as a conceptual data model with fine details on various geological aspects and is based on various general concepts and standards of (geo) data modelling. This is a solid approach from a data modelling point of view, but requires a great deal of prior knowledge and a very good understanding of all these concepts to be able to interpret the GeoSciML data model. However, the understanding of this data model is often difficult to achieve for people with little specialised knowledge of data models, making it difficult to communicate the technical issues.
For this reason, a so-called transfer model is introduced for GEOL_BIM. This is a simplified data model compared to the reference model GeoSciML, in which the focus is on the data needed for the immediate objectives of GEOL_BIM. While the basic principles and core classes from GeoSciML are largely identical in the transfer model, various more extensive structures are simplified and certain special cases are not represented. This reduces the technical complexity of the reference model. On the one hand, this enables easier communication and introduction of the data model in the sector. On the other hand, specific technical interfaces for data exchange can be developed with relatively simple structures and tools.

With the GEOL_BIM transfer model, important geological information can be exchanged. The focus of the exchange is on the transfer of information from the "geology" department to the "construction" department for the integration of geological information into a digital construction model. The focus is on the so-called GeologicFeatures, which are used for the actual description of any geological-geotechnical phenomena with their associated properties. The transfer model contains the following aspects (submodels):

- GeologicFeatures: The classes related to GeologicFeature are the central part of the data model. They allow the description of the geological-geotechnical subsurface with its properties.

- Collection: Collections allow the grouping of GeologicFeatures. Collections define the type of representation of the geological model (e.g. 3D model, cross section, borehole profile, voxel). The basic structures of the data model (in particular GeologicFeatures) are used for all types of representation; specific classes are also implemented for voxel and borehole profile representations.

- Borehole: The borehole profile allows the mapping of geological information in the form of borehole profiles (intervals along the borehole axis) as well as the description of supplementary information on the borehole itself.

- Voxels: Voxels, like borehole intervals, are a special form of representation of the subsurface and are therefore understood as a special form of geologic features. They are defined separately in the transfer model to enable the simplest possible technical exchange of voxel data.

- Observations and Measurements (O&M): O&M is used to map pure measurements or observations for which no direct reference to a specific GeologicFeature is defined.

In the data model, only very few explicit attributes are deliberately defined for the classes. The generic class Property is used to describe any geotechnical properties. This open, generic approach allows the desired high flexibility for individual, project-specific applications of the data model. Outside the data model and in addition to it, a catalogue of properties is kept, which makes implementation recommendations for the most frequently used geological-geotechnical properties (standard properties).

Transformation rules are defined for the transition from the transfer model and reference model GeoSciML to IFC. This specifies how the information from the geological data models can be transferred to the construction-specific standard IFC. For this purpose, both the mappings to the new version 4.3 and version 4.0 of IFC are shown.

Two possible solutions are shown for mapping the uncertainties associated with geological information. The uncertainties can be mapped attributively on the one hand and geometrically on the other. Both approaches are supported by the transfer model. For a systematic and more consistent representation of uncertainties, further data structures should be introduced in the transfer model.

1.2.2 GEOL_BIM interface

Based on the semantic and conceptual principles of the reference and transfer model, GEOL_BIM also develops specific implementations for the transformation of geological data into IFC format. For this purpose, on the one hand a data transfer format is defined and on the other hand suitable adapters for the transformation of the data from the transfer format into the IFC format (technical GEOL_BIM interface).

The software landscape commonly used in Switzerland today for processing geological information and developing geological models is very heterogeneous. There is also a lack of uniform data exchange formats and data structures. Under this prerequisite, relatively simple structures and formats are deliberately used for the transfer format of GEOL_BIM. For the prototypes developed in GEOL_BIM, Excel and some established vector formats are used as the data format for the transfer of geometric information. These simple structures allow the transfer of geological information from many different expert software packages via their export interfaces (e.g. csv exports) as well as manual input and processing directly in the interface format.
Depending on the type of geometric representation of the geological information, different adapters and processing logics are used. While the geometries of boreholes and voxel models are generated directly from the database, geological boundary surfaces can be exported and processed as obj, stl, ts and dxf (selected variants) from geological software.

For easy handling of the transformation functions, the adapters developed in the programming language Python are also made available via a web application. This application enables a low-threshold entry, as no local installation or programming knowledge is necessary and the application guides users through the application. Such low-threshold access to the transformers is an important prerequisite for the acceptance and use of the functionalities, which was realised at the request of the practical partners of the project and was not foreseen in the original project plan.

1.3 Case studies

The results produced within the framework of the GEOL_BIM project were developed on the basis of feedback from experts from monitoring groups and validated and optimised with specific data from use cases from various practical projects. The practical projects deal with use cases from tunnelling, construction sites and natural hazards (permanent landslides).

1.3.1 SIA 199 using the example of the second tube of the Gotthard road tunnel

In this use case, innovative approaches were tested to demonstrate how SIA 199-compliant tunnel strip representations for exploring the rock mass can be integrated into digital construction models. For the second tube of the Gotthard road tunnel, a geological 3D model was reconstructed from existing maps, horizontal and vertical profiles and this was attributed with geological, hydrogeological and geotechnical properties according to SIA 199. Through various visual 3D representations in BIM viewers, the benefit of the joint representation with construction information could be demonstrated.

1.3.2 Insertion of a pedestrian subway at Muttenz railway station

The staging of excavation phases was experimented with, using the example of a synthetic geological model of a pedestrian subway at Muttenz railway station. Using a terrain model mapped by drone images as a starting point, volume calculations for the excavation masses of the construction pit were automatically generated, among other things. For the geological units, some relevant geological-geotechnical properties were selected and transferred to the digital construction model. Various representations were used to demonstrate the benefits of a combined representation of both geological and structural information.

1.3.3 Geological models in deep and underground mining

In this application example, the observations from numerous short borehole intervals were processed into a facies model. Results such as percentages of lithotypes, bed thicknesses or their uncertainties were transferred to a digital construction model. It could be shown that even complex scenarios, including their uncertainties, can be mapped.

1.3.4 Results from finite element models in IFC for the new school building in Renens

For the transfer of results from finite element models into digital structural models, two methods could be demonstrated and tested. In one case study, the results of the calculation of bedding stiffness were transferred into voxel models. In a second case study, new geometric bodies were generated from the results of settlement calculations, each representing a range of values. The results of both approaches were then transferred to IFC and integrated into digital building models on a test basis.

1.3.5 Building protection against permanent landslides near the Chratzera landslide

In this use case, a geological 3D model was developed in which the properties specifically relevant to landslides were incorporated. The model was visualised in BIM viewers via IFC. In addition to the development of the geological model, the process flows for optimal building protection against permanent landslides were also considered in this use case and an ideal process flow was proposed.

1.3.6 Landslides in the digital building model – Brienz GR project

In this use case, the transfer of information on hazards and intensities from gravitational processes into BIM software was demonstrated, so that these can be made more usable over the entire life cycle of a structure. Monitoring data during the operational phase of the structure are of central importance. The measurement data could be used to trace mass displacements from the operational phase back to the original geological model. For this purpose, a geological-geotechnical model of the landslide surface was developed and some geotechnical parameters relevant for monitoring were identified. The geological model of the landslide, which was converted into a BIM model, was used for communication with cantonal authorities, among other things.

1.4 Conclusion and outlook

With the transfer model and the reference model, GEOL_BIM provides conceptual foundations on the basis of which elementary geological and geotechnical information can be exchanged in a structured way. These conceptual data models form the foundation for the common understanding and harmonisation of geological information within geology and across its borders to other construction disciplines.

Within the framework of GEOL_BIM, tools based on these data models were developed and tested using practical examples. The IFC results generated with the workflows can be imported, processed and visualised in common BIM software products. The interface and the adapters were validated with the data provided by the project partners. Despite the technically heterogeneous case studies, it was possible to define common requirements for the exchange of information. The basic requirements include the structured transfer of borehole information and information linked to geological structures, units or voxels. Based on the international standard GeoSciML, there are few or no Switzerland-specific structural requirements.

Nationally specific requirements arise primarily in the area of value range definitions of classification systems. Examples of this are regionally logical designations such as formation names or their colour coding.

The international IFC standard is geared towards building construction. Standardised data exchange in civil engineering is only possible to a limited extent. Geology and geotechnics are only partially mapped. Nevertheless, the GEOL_BIM transfer model has succeeded in transferring geological information to IFC by means of a strong simplification in order to represent it there in the digital building model.

With regard to spatial queries and the visualisation of models, the currently available, established BIM viewers are also oriented towards structural engineering. Compared to the possibilities offered by geological modelling software, there is a lack of spatial queries optimised for the subsurface, efficient visualisation options or the possibility to dynamically colour areas of the subsurface based on parameters. Efficient visualisation options also include the requirement to be able to generate geological profiles along arbitrarily curved lines in space. The optimised representation of data-intensive geological models, such as voxel models, will also be an essential requirement in the future.

However, requirements such as attaching properties to the supporting points of geometries are also extremely relevant – something that is currently supported neither by IFC nor by BIM viewers. Basically, the question must be asked and clarified as to what level of detail of geological information must be present in a BIM model at all. There is also the question of which geological base data and standards are still considered part of a project and to what extent technical decisions must be fully traceable during the development of geological 3D models. Depending on the delineation of workflows, only a very small part of geological information may need to be transferred from 3D modelling software to a digital construction model for collaboration. The visual analysis of geological models is generally of great importance here. It remains to be evaluated in which use cases machine-readable and automated evaluations offer added value for collaboration. For example, the (partially) automated quantification of excavated materials according to criteria such as reusability or disposal requirements is conceivable.

Even though GEOL_BIM is broadly positioned with 15 project supporters and practical projects from three different application areas, only a few aspects of geology could be examined in more detail. Further practical projects with a different focus should follow, especially interdisciplinary topics such as hydrogeology. With GroundwaterML, there is an extension for GeoSciML that could serve as a suitable starting point here.

Geological 3D models are created in object-oriented modelling tools. In order to be able to connect as many different proprietary software packages as possible, the object geometries were exported to open formats and the object information to Microsoft Excel for transfer via the GEOL_BIM interface. In this step, the object orientation of the 3D modelling software is largely lost – a media discontinuity that should be avoided in the future. The next step should therefore be to evaluate how geological information can be exchanged in the future from proprietary software according to harmonised standards, independently of system and manufacturer.

The GEOL_BIM data model is a first step towards a harmonised data exchange of geological information for collaboration in construction projects. Building on this, innovative processes can enable the processing and evaluation of geological information without media discontinuity and promote collaborative decision-making in the construction project.

2 Introduction

2.1 GEOL_BIM Innovation Project

The GEOL_BIM Innovation Project, co-financed by the Swiss Innovation Agency Innosuisse, is the first step towards the transformation from analogue to digital planning and management of buildings and infrastructures, including geological conditions. The Swiss Association of Geologists CHGEOL recognised the need for GEOL_BIM. The project is being carried out in collaboration with the Swiss Geological Survey swisstopo and the Institute for Virtual Design and Construction at the University of Applied Sciences and Arts Northwestern Switzerland FHNW. The project management of the GEOL_BIM Innovation Project has been assigned to CHGEOL.

In early autumn 2019, a number of representatives from the private sector, authorities and associations also declared their support for the GEOL_BIM Innovation Project to the CHGEOL in written letters of intent. In addition to the parties involved in the application, CHGEOL, swisstopo and FHNW, the Swiss Association of Geologists is also coordinating the monitoring of the project by various supporters from the private sector, authorities and associations. This body ensures the practicality of the solution developed with one representative from each of the supporting organisations in the advisory group. The advisory group members provide GEOL_BIM with data and documents from their own projects for research purposes within the framework of the innovation project or identify third parties to take on this task. The contributions promised by the project supporters for the personnel and financial support of GEOL_BIM were compiled and recorded in individual contracts. Each supporter has also already contributed a project idea in the form of a practical project along with their declaration of intent to participate in GEOL_BIM. The supporters have thereby already actively helped in the application phase to identify the areas of application for which there could be a future increased need for the exchange of geological information in the context of cooperation in construction projects.

Swiss construction culture is also actively shaping the digital transformation of Swiss society. Geologists have been valued and indispensable partners in construction projects for centuries and are thus an integral part of Swiss construction culture. GEOL_BIM is trying to help geological expertise achieve greater visibility in an increasingly connected world. Both the digital competence of individuals and that of the community should be equally promoted to shape the digital transformation in the future.

2.1.1 Overall project goals

2.1.1.1 Objective

The GEOL_BIM Innovation Project aims to integrate geology into the application of the BIM method (Figure 1). In development is a manufacturer-independent, system-neutral and open interface between geology and digital building models. The creation of such an interface, taking geological uncertainties into account, should facilitate more efficient cooperation and communication in the construction process in the future (e.g. between client and geologist or between geologist and engineer). The current working model involves exchanging the results of geological investigations, modelling and evaluations on paper. Although a multitude of computer-based systems in geologists` work, information exchange today leads to media discontinuities and irreversible losses of information, so that there is no real digital continuity of information. Interoperability between different geological software applications and BIM software is hardly realised, if at all.

Figure 2 illustrates the conventional transfer of geological information from geologists to engineers and compares this with a data and information exchange via digital construction models. The illustration shows how the model-based communication of results could prevent disruptions in digital continuity in the future.

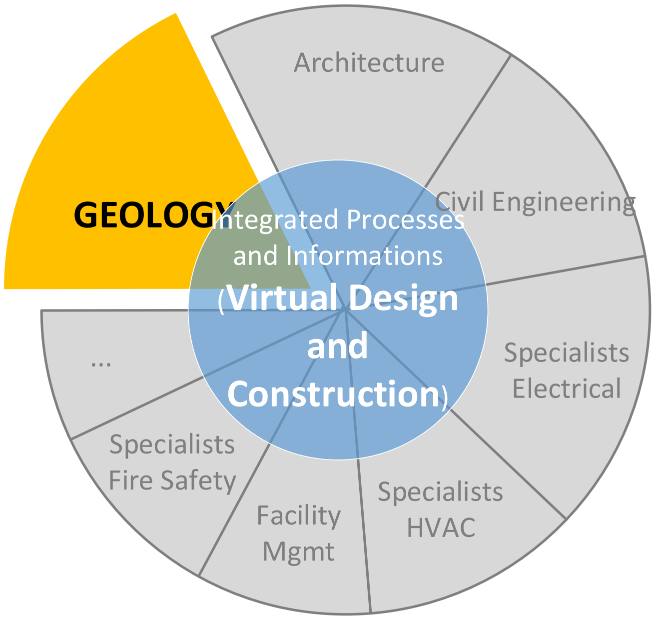
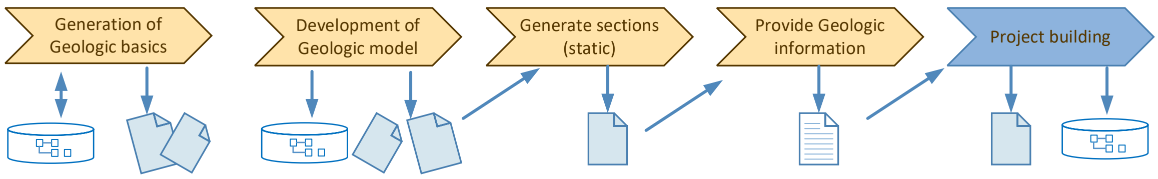
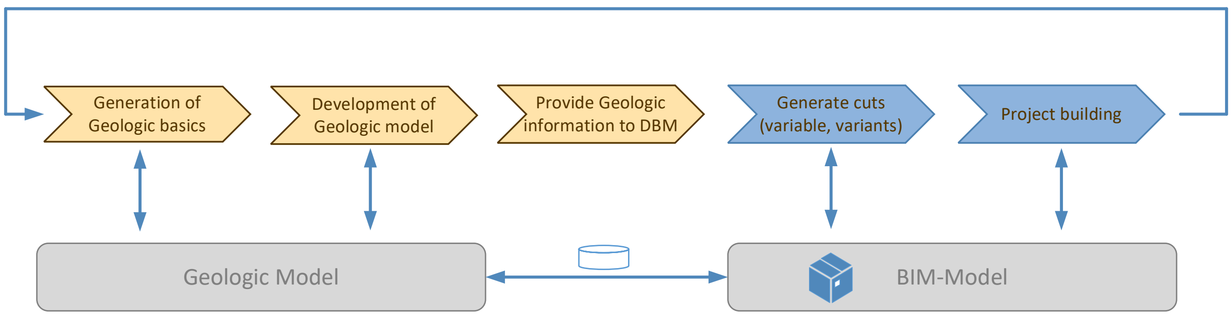


Figure 1. Integration of geology in the application of the BIM method.

Process conventional:
- many discontinuities, no standards, document-based
- Static generation of sections in geological model (manually)



Process GEOL_BIM:
- Model-based, consistent, end-to-end data management, standardised interfaces
- (Dynamic) generation of sections in BIM model (combined with building data)



Legend

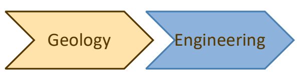


Figure 2. Simplified representation and working hypothesis for the model-based transfer of geological information in the construction process.

2.1.1.2 Expected results

The results expected from GEOL_BIM include data models, workflows, guidelines, standards, best practice examples, an implementation concept and first attempts to implement programming scripts and applications for the implementation of the described interfaces. Beyond GEOL_BIM, it should be possible to integrate the data and information regarding the geological conditions relevant for a building into the BIM models of engineers, architects and building managers to promote interdisciplinary cooperation. The increasing international standardisation of data exchange and the associated processes is a basic prerequisite for the digital transformation. On the other hand, it is necessary to take into account country-specific needs and legal requirements, and to reflect them in the data models and implementation concepts.

With an eye towards improving the current state of science and technology, the following three points are to be further advanced with the help of GEOL_BIM.

1. The designing of semantic and conceptual data models, workflows, guidelines, standards and best practice examples for the integration of geology into the BIM method.

2. Concretisation of national needs for the adaptation of international standards to the country-specific requirements of Switzerland.

3. Development of implementation concepts and prototype realisations of vendor-independent, system-neutral and open interfaces for the integration of geology into the BIM method.

2.1.1.3 Target audience

The GEOL_BIM Innovation Project is an interdisciplinary project with a correspondingly interdisciplinary target audience. GEOL_BIM is aimed not only at the project supporters, advisory group members and all project participants, but also at clients, planners, architects, engineers, the Swiss geology scene and all with an affinity for the Swiss geology and construction industry or civil engineering. GEOL_BIM is also aimed at all those who have an interest in the interdisciplinary exchange, integration and communication of data and information on construction projects in the future.

2.1.2 Technical goals

2.1.2.1 Objective

In addition to the overall GEOL_BIM Project goals, the project application for the innovation project defines technical goals for the integration of geology into the BIM method.

- Geological data and information, such as profile sections along a tunnel axis or through an excavation, will in future be exported from a specialist software via a transfer model and can then be imported into commercially available BIM software.

- The imported transfer model enables simple quantity calculations for variant studies in BIM software (authoring and analysis software) without having to return the information to the expert software. The aim is not to replace the analysis capabilities of expert software or to implement them in BIM software (compare with section 2.1.3). Quantity calculations are limited to the quantification of output-relevant properties of geological result products for variant studies.

- Uncertainties associated with geological models are transferred to the BIM software, they can be accessed at any point in the model and can be displayed graphically.

- The data exchange from the expert software to the BIM software occurs using the international standard of the Industry Foundation Classes (IFC) and should be compatible with the IFC 5 version that will be available in the future. Based on this, country-specific extensions are being developed for Switzerland to cover the specific regional requirements in a practical way.

- The data exchange is technically specified with an XML-based Model View Definition mvdXML.

- The developed solutions are tested with different software tools (prototypical) in three use cases.

2.1.2.2 Expected results

According to the project objectives described in section 2.1.1.2, a distinction can be made between data models, specifications and implementation concepts.

Concepts, data models and specifications (interface descriptions)

- The specifications of a data model of the necessary geological fundamentals (Geology+) form the basis of a manufacturer-independent and system-neutral transfer model for exchanging geological data and information.

- The specifications of a geological 3D model (Geology+) form the basis of a manufacturer-independent and system-neutral transfer model for the exchange of geological data and information.

- Based on the aforementioned specifications (Geology+), an XML-based model view definition (mvdXML) is to be generated for mapping Switzerland-specific requirements in the exact application of the IFC standard.

Implementation concepts (prototypical scripts or software tools)

- Export modules (adapters) for exporting geological data (3D model and application area-specific data and information) from expert software.
- Transformation modules for converting exported geological data to IFC.
- Import modules (adapters) for importing geological transfer models (including 3D model and application area-specific data and information) in IFC into BIM software.

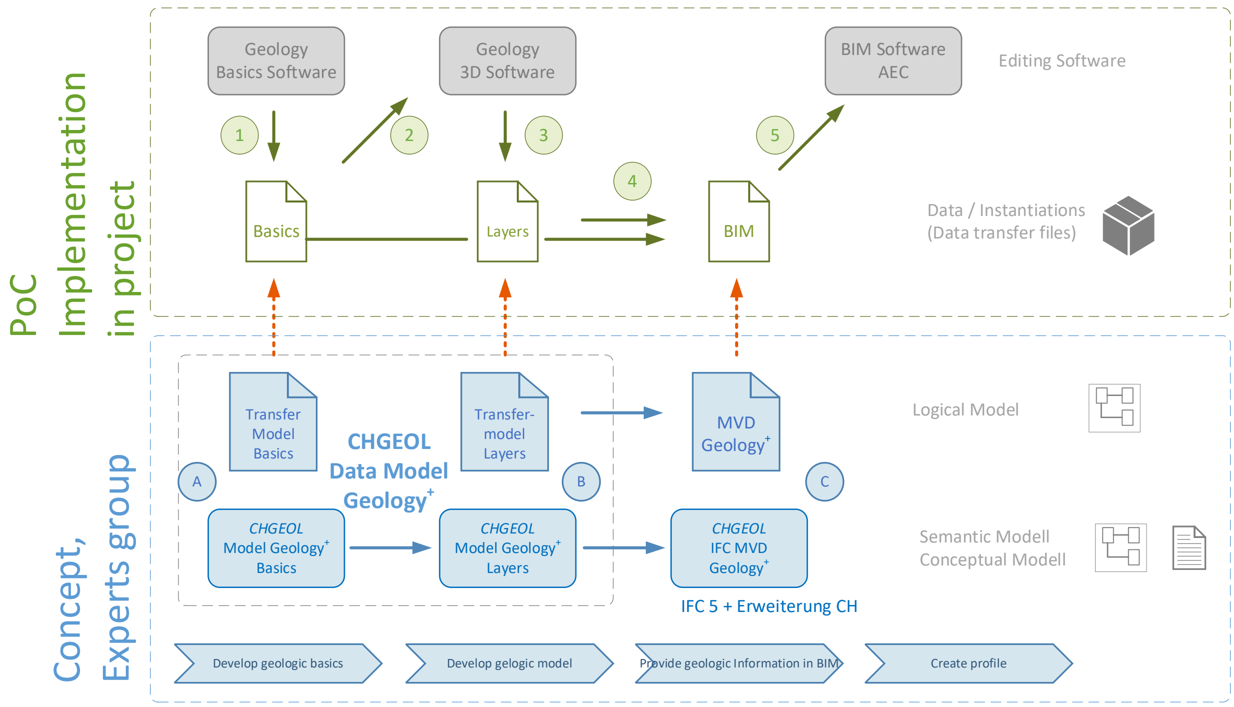


Figure 3. Overview of the results to be implemented. Abbreviations: Basics (GL), Digital Building Model (DBM), Industry Foundation Classes (IFC) and Model View Definition (MVD).

2.1.3 **Delimitation**

2.1.3.1 NON-goals

The following list exemplarily formulates what are NOT the objectives of GEOL_BIM. This list thus stands in contrast to the goals formulated in section 2.1.2. This formulation serves the sole purpose of creating clarity and preventing misunderstandings.

- There are many different approaches to modelling geological information in three-dimensional space. GEOL_BIM has no ambitions to design new modelling paradigms to compete with the existing ones. The sole aim is to show which aspects of existing modelling paradigms are relevant for integrating geological information when applying the BIM method in the future.
- In the areas of data and information exchange and management, many different paths lead to the desired result. There is no intention to prescribe how a goal will be achieved. The choice of the appropriate methodology will remain at the expert`s discretion. GEOL_BIM merely attempts to harmonise the criteria that must be met to enable an open and standardised exchange of information.
- Specialist expert software still has its justification and GEOL_BIM has no ambitions to replace it. It is also not the aim to integrate the functionalities of specialist software into BIM software in the future. It is exclusively about enabling open interfaces by ensuring that the data structures for data and information exchange are harmonised.

- Viewed as a whole, geology as a discipline must collect and process a multitude of relevant data and information. In no way does GEOL_BIM aim to achieve a complete compilation of all relevant aspects. On the contrary, the intention is to focus on precisely those aspects that are essential for specific applications relating to a building. In the sense of a 'proof of concept', GEOL_BIM should provide the basis for the future development of other aspects.

- When talking about geological uncertainties, it is not the aim of GEOL_BIM to prescribe the mathematical solution methods for calculating uncertainties. How uncertainties are calculated or estimated will remain an issue for the expert in the future. GEOL_BIM is only concerned with the manner in which uncertainties can be communicated within the framework of information exchange.

2.1.4 Methodology

One or more interviews were conducted with all members of the accompanying group to compile the basics and to define the requirements. In addition to structured questions, personal goals and possible practical applications were discussed in the interviews. The findings from the interviews and the literature research were incorporated into the two fundamental reports on geology and the BIM method (in German).

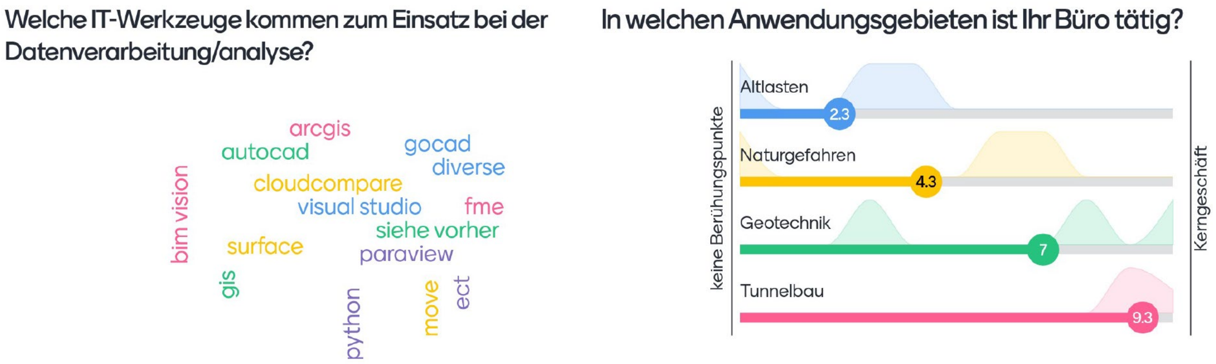


Figure 4. Advisory group survey during the interview phase. Left: What IT tools are used for data processing and analysis? Right: In which application areas is your office active?

Once the basic phase was completed, the conceptual description of the solution approaches was discussed and elaborated in joint workshops for the different application areas. Implementation of the three created adapters was validated with the advisory group and tested in various practical projects. The findings from the validation were incorporated into the further development of the adapters and are available in the web application.
The data model was discussed in the core team and analysed with the existing practice data by the core team. Together with the fundamental reports, the documentation of the data model and the further training concept, this final documentation forms the report portfolio of the GEOL_BIM Innovation Project.

2.1.5 School of continuing education concept

The concepts and web application developed in the GEOL_BIM Project are to be suitably introduced to the professional world of geologists and other participants in the planning and construction process. A school of continuing education and training concept is being developed for this purpose. The concept shows which aspects of GEOL_BIM could be introduced in practice and in what form. Technical and didactical basics are defined. Costs, financing and organisation are outlined. Processing of the project findings in publications, in particular technical articles for direct dissemination in the geology and "BIM" specialist community. The final school of continuing education concept will not be made publicly available.

2.2 Common language

2.2.1 Saying and understanding the same thing

To achieve a common understanding, it is important to create a shared glossary. It is important to bear in mind that a key factor for joint success in interdisciplinary teams is a common language and shared understanding.

For a common understanding, it also helps that the corresponding disciplines agree on a uniform and consolidated terminology. In the case of buildingSMART Switzerland, a "National Glossary on Digitalisation in the Construction and Real Estate Industry" was made available. The glossary provides a uniform terminology for digitalisation in the planning, construction, operation and dismantling of buildings. The glossary is being continuously expanded and will be available in German, French and Italian (Glossary Bauen Digital Schweiz, 2021). The glossary can be accessed through the following link: https://bauen-digital.ch/de/produkte/glossar/.

In addition to the national glossary, the Institute of Digital Construction of the FHNW maintains an online glossary pertaining to the BIM method. The glossary describes terms and definitions that go beyond the scope of the national glossary and could be relevant and useful in the context of education, training or practice. The glossary can be accessed through the following link: https://fhnw.ch/vdc-glossary.

2.2.2 List of abbreviations

BEP:	BIM project execution plan
BIM:	Building Information Modelling
BSI:	Building Smart International
CHGEOL:	Swiss Association of Geologists
DF:	Breakthrough fans
DR:	Breakthrough partitions
FEM:	Finite element method
FHNW:	University of Applied Sciences and Arts Northwestern Switzerland
GeoSciML:	Geoscience Markup Language
GUI:	Graphical user interface
IDIBAU:	Institute of Virtual Design and Construction
IFC:	Industry Foundation Classes
INSPIRE:	Infrastructure for Spatial Information in Europe
OGC:	Open Geospatial Consortium
OSM:	Upper freshwater molasse
RG:	Channel belt facies
SQL:	Structured Query Language
UI:	User Interface
UPS:	Flood plains, palaeosols and marshes
UW:	Embankments
YAML:	Yet Another Markup Language

3 Challenges

3.1 Data model for geology

For geological data to be transferred efficiently and sustainably to IFC, it is essential that this data is available in a structured form - standardised. Structured data management in turn requires an underlying data model that meets the requirements of the data to be transferred. The ideal case would be access to a geological data model that covers the entire spectrum of geological data to be processed and, if possible, is already in widespread use. A well-founded analysis of existing international and national geological data models was already carried out in the fundamental report (Schneider et al., 2021, in German). The analysis showed that international geological data models exist (GeoSciML, INSPIRE GE, AGS), but that they do not individually cover the entire spectrum and have hardly been used in Switzerland to date. National geological data models developed by swisstopo have also been published. These are currently limited to the published data models DM Borehole Data and DM Geology. Further data models are being developed. In the GEOL_BIM Project, the challenge in this respect lies in the development of a conceptual data model that takes existing standards into account to the greatest degree possible and, at the same time, takes into account all classes and attributes that are necessary for the description of the relevant geological data (geometry and attributes).

3.2 Requirements for geometry and information management

Geological data consists of different types of information (measurements, borehole logs, modelled surfaces, 3D models, etc.). This diversity is also reflected in the variety of geometric types that are regularly used by geologists and geological expert software (e.g. points, lines, polygons, surfaces, volumes, 2D and 3D grids and other decomposition models).

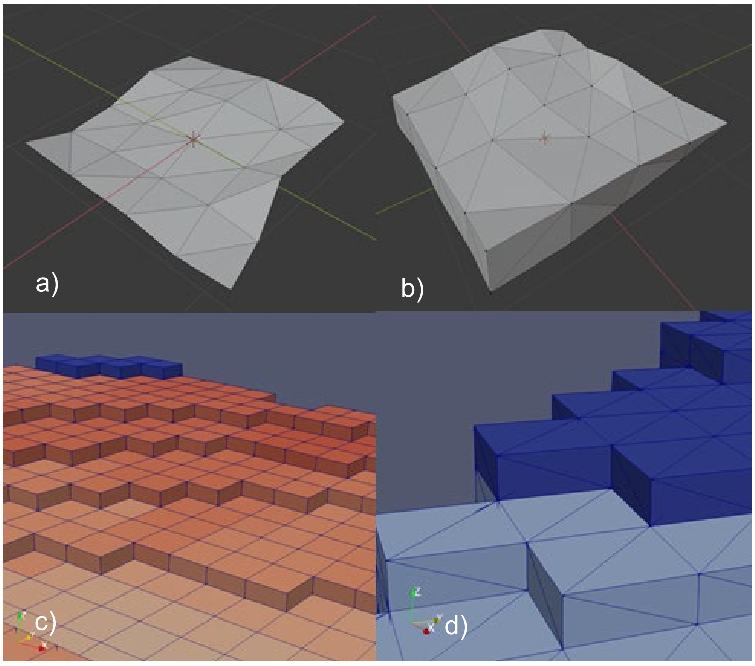


Figure 5. Examples of different types of geometry. These are triangular meshed networks or voxel models which can be generated and visualised in geological expert software. a) Triangulated irregular Network (TIN), b) Boundary Representation, c) Voxel, d) Tetraether.

IFC is dominated by the representation of geometry as a Boundary Representation (B-Rep) (Figure 18, Fundamental Report, BIM Method (Schneider et al., 2021, in German). Challenges arise in the visualisation of some geological data that cannot be translated directly into a boundary representation and/or are not typically represented (rendered) in this way in geological software.

Geological expert software makes it possible to define geometries as lines or points, but to display them as tubes or cuboids, for example, for visualisation and analysis purposes. In order for these geometries to be displayed accordingly in BIM viewers, the objects must first be converted into boundary representations so that they are available as actual volumes. For example, boreholes in geological expert software are usually defined as 3D lines and displayed as 3D volumes (pipes) via a rendered buffer surface. In the IFC structure, this borehole must be defined as a boundary representation of the actual 3D volume (tube). Similarly, in geological software, voxel models are usually defined by the voxel centres, with a 3D buffer surface rendered at each point for visualisation to obtain a cuboid (voxel). In IFC, however, each voxel must be explicitly defined by its boundary representation.

The variety of data formats depends not only on the variety of geometry types, but also strongly on the geological expert software used (Figure 6). These are independent products that also have their own data formats. This results in a large number of data formats, not all of which can be considered for the transformation to IFC. It is thus important to support those data formats that are supported by the majority of geological software products. In addition to the most common export formats, open formats should also be preferred (Volken et al., 2020).

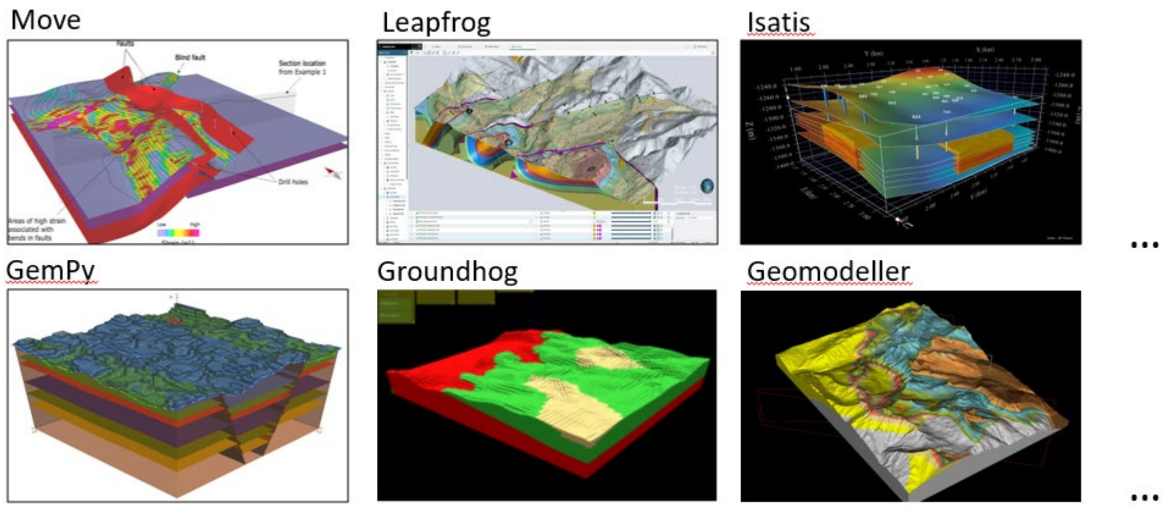


Figure 6. Examples of 3D geological models from six different expert products. Limitations of the visualisation of geological data in the BIM viewer

3.3 Limitations when geological data is visualised in BIM-viewers

Expert geological software is often highly specialised when it comes to creating a 3D environment in which complex geological geometries can be visualised and analysed, incl. spatial queries. The focus is on colouring and spatial analysis, as well as the "on the fly" creation of well-aligned profiles for large datasets. BIM viewers, on the other hand, are geared towards the visualisation and analysis of buildings and building elements. Efficient properties queries of the individual components are central. The sections through the structures usually run along the building axes or the section direction is defined based on planes of existing components (e.g. façade elements). It is therefore hard to obtain a more complex, arbitrarily oriented section generation (e.g. also bent sections) in existing BIM viewers. The fact that the underground is (almost exclusively) a filled space and that, in contrast, buildings consist to a large extent of (hollow) spaces, also points to different requirements in terms of visualisation and analysis tools.

The large quantities of data that can arise during the generation of complex geological geometries often represent a major challenge. As opposed to geological expert software, the currently available BIM viewers are incapable to deal with such a high data load. If one looks at a voxel model, for example, this can be efficiently visualised, analysed and saved as a 3D matrix in some expert software. In IFC, each voxel must currently be available as a cuboid so that it can be visualised and queried, which has a negative impact on the amount of data and performance for correspondingly large voxel models.

3.4 Dealing with uncertainties in the digital building model

The topic of uncertainties in geology is very broad. The challenge of how to determine uncertainties in geology is not comprehensively dealt with in the GEOL_BIM Project, as this would go beyond the scope of this documentation. The focus is on the challenge of how the uncertainties that are already determined can be visualised and communicated to others.

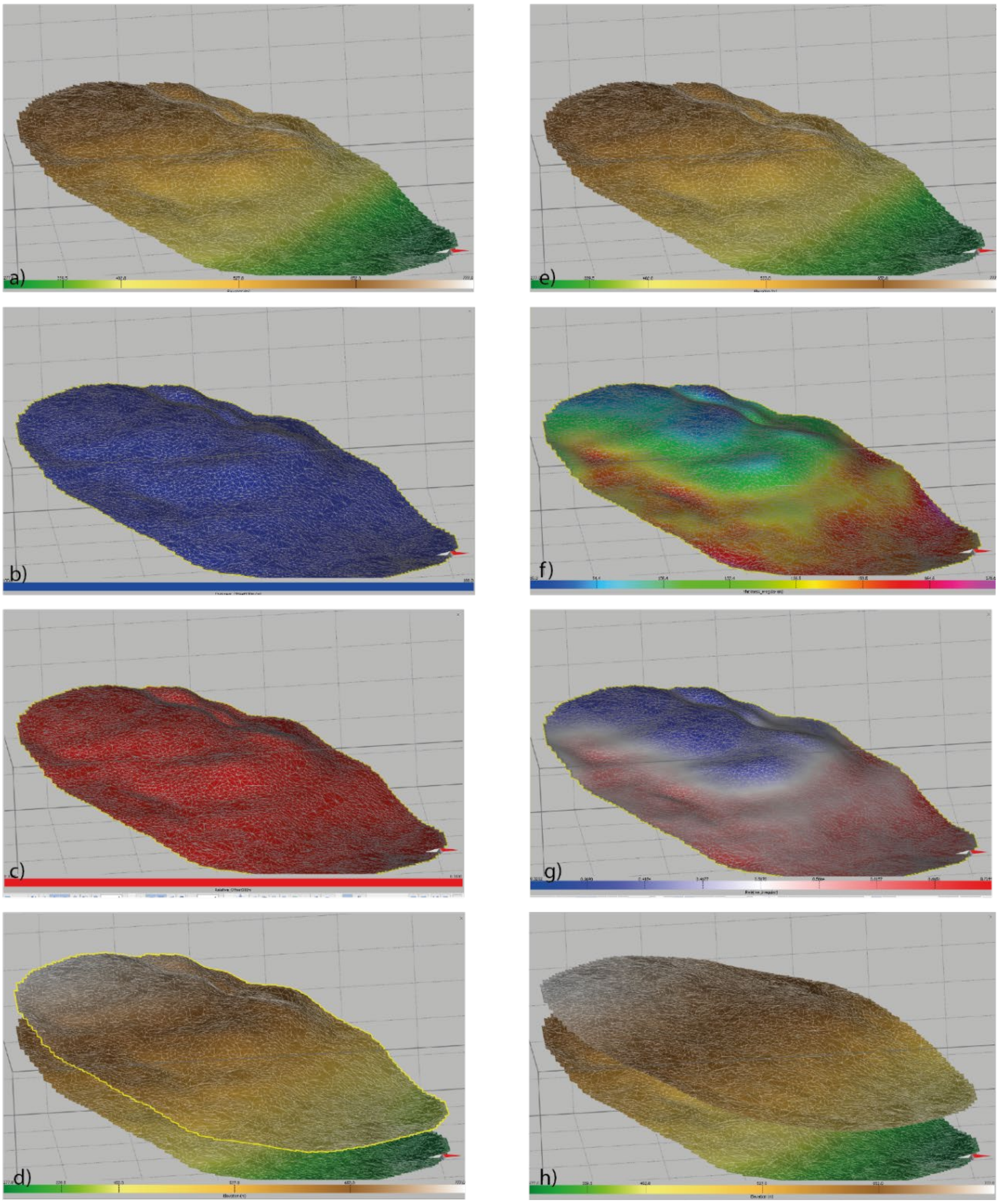


Figure 7. Variants for the representation of uncertainties in 3D. A 3D surface (a, e) with maximum height variability as uncertainty component. The uncertainty is represented for the object (left column) or per vertex (right column) either as a maximum value in metres (b, f) or as an uncertainty index between 0-1 (c, g) or finally as additional geometry representing the surface of the maximum height (d, h).

Two categories can be distinguished: Either uncertainties in geographic information are defined as i) an **uncertainty value** (e.g., minimum to maximum value or relative probabilities, etc.) related to an object (point, line, surface, etc.) in space, or ii) as a geometric object. These categories are not mutually exclusive, but are two different approaches to the same problem. If the height uncertainties of a surface are considered, two categories can be distinguished. i) An absolute numerical value (a) describing the amount of maximum height variation of a surface X in metres. Or (b) a value between 0 and 1, indicating the reliability that surface X is at the correct height. ii) Alternatively, it is possible to have a separate **geometric object** at a distance from the original surface X that describes its maximum height deviation.

Depending on how geologists choose to deal with uncertainties, the visualisation in case i) can be accomplished by colour coding the uncertainty values stored in the geometry. As previously mentioned, BIM visualisations are somewhat limited in colouring (e.g. by a colour ramp or a legend). In case ii), additional geometry can be uploaded describing the uncertainty of an object to which it belongs. Which method is most appropriate depends on what the uncertainty describes and what it will be used for later. It is up to the Geologist to decide which method is most appropriate from case to case.

Another challenge related to uncertainties in the GEOL_BIM Project is the lack of digital data containing uncertainties made available for the project.

4 Applied solution approaches

4.1 Data model

4.1.1 Meaning of the "GEOL_BIM" conceptual data model

In the GEOL_BIM Project, a conceptual data model is being developed in which the relevant aspects are defined and described in a system-neutral and formalised way. The conceptual data model represents the common basis for understanding. It represents an abstraction of "reality" (reality) by identifying and defining the relevant aspects. This is accomplished - as in any modelling - by means of a (domain-specific) focusing and simplification or abstraction of reality.

Figure 8 illustrates the significance of the conceptual "GEOL_BIM" data model for the flow of information or data processing.

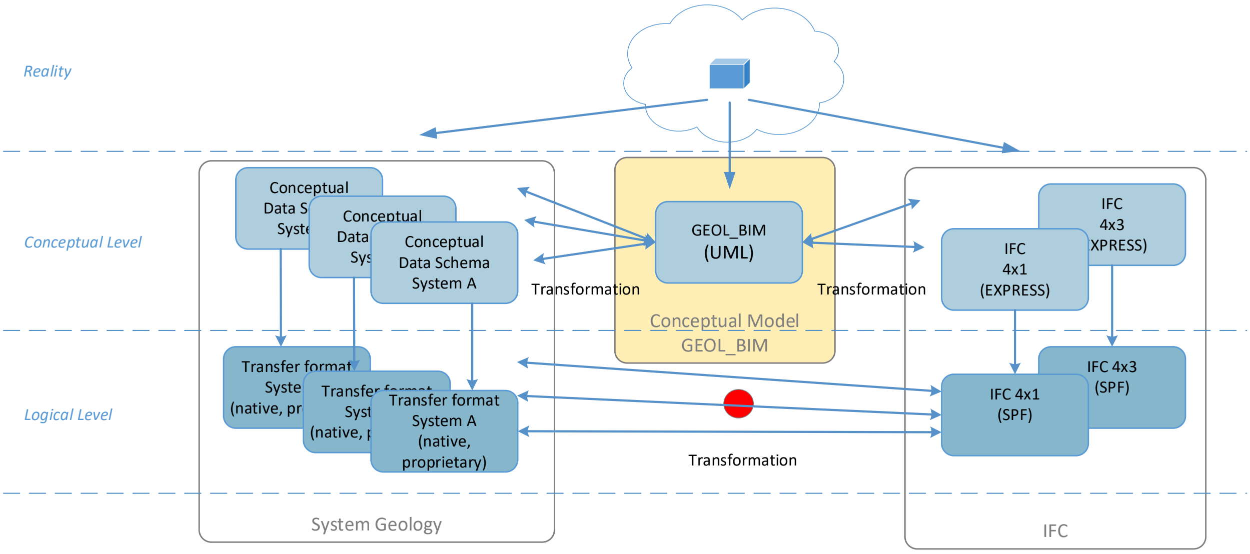


Figure 8. Model transformations and design levels.

The various systems, applications, formats and standards each have different goals and tasks (geology systems). Although they all deal with the topic of "geology", they focus individually on different aspects of reality and also represent these differently in their respective data models. This means that they have specific conceptual data models. Depending on the system, these conceptual data models are logically implemented in different technologies and formats (logical levels).

For a systematic exchange of information or integration of information to take place, the different conceptual data models must be related to each other ("translation" or transformation between the models). The conceptual data model "GEOL_BIM" is being developed for this purpose. The intention is also to establish a common definition of the (relevant) "geology" that is understood by all participants and defines a common understanding of the technical and conceptual aspects.

The different conceptual data models of the geology systems can (ideally) be transformed (translated, mapped) into the "GEOL_BIM" conceptual data model and, in turn, the (integrated) information can be transformed into further conceptual data models. The primary focus is on the transformation into the IFC data model. Different versions of IFC (with data models that differ in detail) can be distinguished here.

The transformations at the conceptual level primarily pertain to the translation or transfer of similar technical concepts between different models. At the logical level, the technical and format-related properties of the different systems also play a role (e.g. transformation of csv structures, xml structures in SQL databases or the Step Physical File format of IFC).
UML (Unified Modelling Language), in particular class diagrams, is used as the description language for the conceptual data model. The diagrams are supplemented by descriptive explanations in text form. A brief introduction to the notational form of UML is provided in the separate documentation for the data model (Results Report Data Models).

4.1.2 Transfer and reference model

The fundamentals analysis has shown that the GeoSciML (OGC, 2017a) conceptual data model already takes many technical aspects of GEOL_BIM into account and that this standard has a relatively large international distribution and recognised position, also due to its extensive adoption by INSPIRE. Use case work and analyses have confirmed this initial finding. When defining the data model for GEOL_BIM, GeoSciML 4.1 was therefore chosen as the basis for the reference model. (Hansen et al., 2019, p. 107) defines the role of a reference model as follows: "A reference model is a model that provides an accepted good solution to a commonly occurring problem. The reference model serves as a point of reference for possible further developments of a concrete model that depicts similar problem areas." In this sense, aspects that are already well implemented for the application of GEOL_BIM in GeoSciML are implemented as analogously as possible to ensure a high level of compatibility with GeoSciML. With a reference model based on GeoSciML, the following picture emerges for the GEOL_BIM data models (see also Figure 9):

- On the conceptual level, GEOL_BIM distinguishes between a transfer model and a reference model.
- The transfer model is the model that is relevant to the "outside". It is used for uniform communication between the technical specialists and describes the interface for data transfer from the geology tools.
- The reference model is carried in the "background". It is largely based on the GeoSciML 4.1 data model. Only in justified individual cases is there a deviation from GeoSciML, whereby the basic principles are retained. It is supplemented selectively with other, recognised concepts and principles to meet the requirements of GEOL_BIM as completely as possible. The adaptations are documented so that additions and deviations from established standards are transparent and trackable. These slight adaptations to the original model are designated by "GeoSciML+".

  The transfer model can largely be mapped in the reference model, but represents a simplification of it. The transformation rules are shown and ensure compatibility with the reference model.

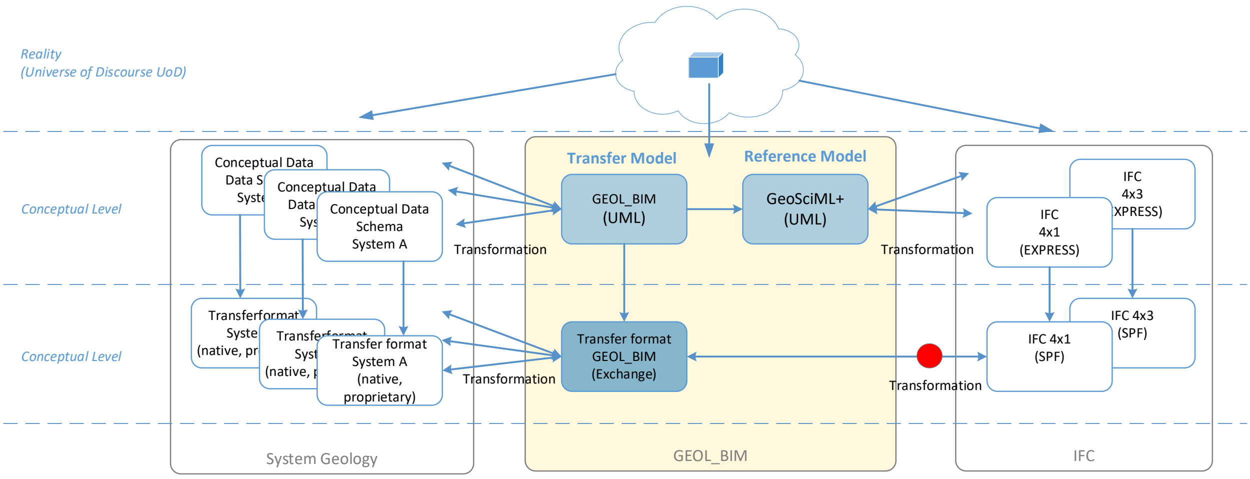


Figure 9. Model transformations with transfer and reference model.

A direct, unadapted application of GeoSciML is out of the question for GEOL_BIM for several reasons:

- With all its extensions GeoSciML covers many details that are not necessary transferring geological information to a construction project. It is therefore appropriate to consider only general basic concepts from GeoSciML for GEOL_BIM.
- GeoSciML is based on various general concepts and standards of (geo)data modelling (ISO-19000 series, including GML, Observations and Measurements, Meta-data). This is a good approach from a data modelling point of view, but requires a great deal of prior knowledge and a thorough understanding of all these concepts to be able to interpret the GeoSciML data model. Understanding this data model is difficult to achieve for people with little specialised data model know-how. This makes it difficult to communicate the technical issues.

- GeoSciML focuses on the field of geology. The fields of geotechnics and hydrogeology are not covered. Extensions to GeoSciML must therefore be made for these disciplines. For hydrogeology, various standards are available to complement GeoSciML, e.g. GroundWaterML (OGC, 2017b), INSPIRE Geology (INSPIRE, 2013).

- It must be assumed that much geological data cannot currently be exported from the geology tools via automated interfaces, but that manual configurations and manipulations are necessary to provide the data, which requires simple formats for data transfer. This means relatively simple data structures with low complexity.

The transfer model addresses these challenges by adopting and following the basic principles and structures of GeoSciML. With regard to the application goals of GEOL_BIM, however, adjustments are made to the following principles as opposed to GeoSciML:

- Reduction to the essentials (less depth of detail).

- Simplification of basic concepts.

- Consideration of the specialist areas of hydrogeology and geotechnics.

- Design for simple data exchange structures (including Excel and CAD files).

The GEOL_BIM transfer model is described in summary form in this report. Both a more detailed explanation of the transfer model and a description of the reference model GeoSciML+ can be found in the separate data model (Results Report Data Models).

4.1.3 GEOL_BIM transfer model

The "GEOL_BIM" transfer model defines simple data structures with which the central geological information can be exchanged. The focus of the exchange is on transferring information from the domain "Geology" to the domain "Construction" to integrate geological information into a digital building model.

The figure below shows an overview of the conceptual class diagram of the GEOL_BIM transfer model. In the class model, five main areas (sub-models) can be distinguished:

- GeologicFeatures: The classes around GeologicFeatures form the central part of the data model. They allow the actual description of the geological-geotechnical subsurface with its properties.

- Collection: Collections allow the grouping of GeologicFeatures. Collections define the type of representation of the geological model (e.g. 3D model, cross section, well log, voxel). The basic structures of the data model (in particular GeologicFeatures) are used for all types of representation; specific classes are also implemented for voxel and borehole profile representations. The collections, as well as supplementary classes (not shown in the overview), enable not only the description of the type of representation but also the description of higher-level information on the geological model and the data stock (project data, metadata).

- Borehole: The borehole section allows the representation of geological information in the form of well logs (intervals along the borehole axis) as well as the description of supplementary information on the borehole itself.

- Voxel: Voxels, like borehole intervals, are a special form of representation of the subsurface and are therefore understood as a special form of geologic feature. They are defined separately in the transfer model to enable the simplest possible technical exchange of voxel data.

- Observations and Measurements (O&M): O&M is used to represent pure measurements or observations for which no direct reference to a concrete geologic feature is defined.

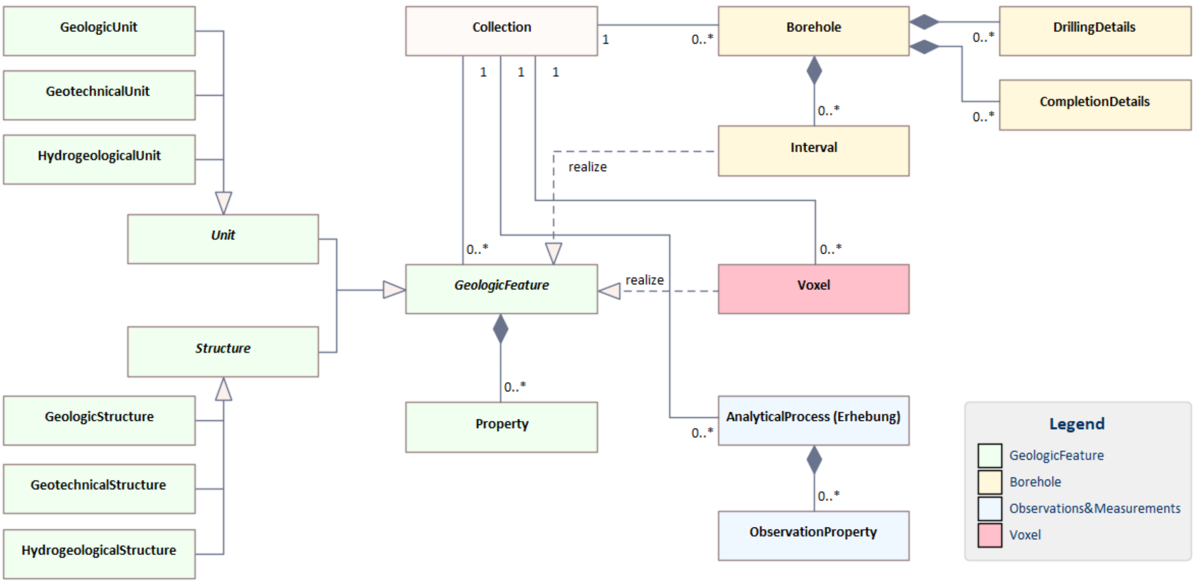


Figure 10. Class diagram transfer model GEOL_BIM as overview. Conceptual view.

The individual areas are briefly explained in the following sub-chapters. A detailed description of the data model can be found in a separate documentation (Result Report Data Model).

4.1.3.1 GeologicFeature

The description of the subsurface is generally made using so-called GeologicFeatures. A GeologicFeature is an abstract class for the description of basically any geological phenomenon. The GeologicFeatures are distinguished according to two main types: Either the geological phenomenon is a **unit** or a **structure**.

- A ***unit*** is a spatially definable area of the subsurface with uniform properties. Units are defined for the purpose of exploration or investigation depending on the respective question and the properties under consideration. The geometric expression of a unit is a body[1]. Based on this, the term "envelope" is understood as a synonym for unit.

- A ***structure*** subdivides the subsurface according to structural criteria. Structures are defined for the purpose of exploration or investigation depending on the respective question and the properties under consideration. The geometric expression of a structure is a surface (in space)[1]. Based on this, the term "boundary surface" is understood as a synonym for structure. Several neighbouring structures can be combined as a unit.

[1] Refers to the abstracted real-world object. Reduced geometric expressions derived from it are possible depending on the form of representation (e.g. 3D model, 2D plan, 3D section, etc.).

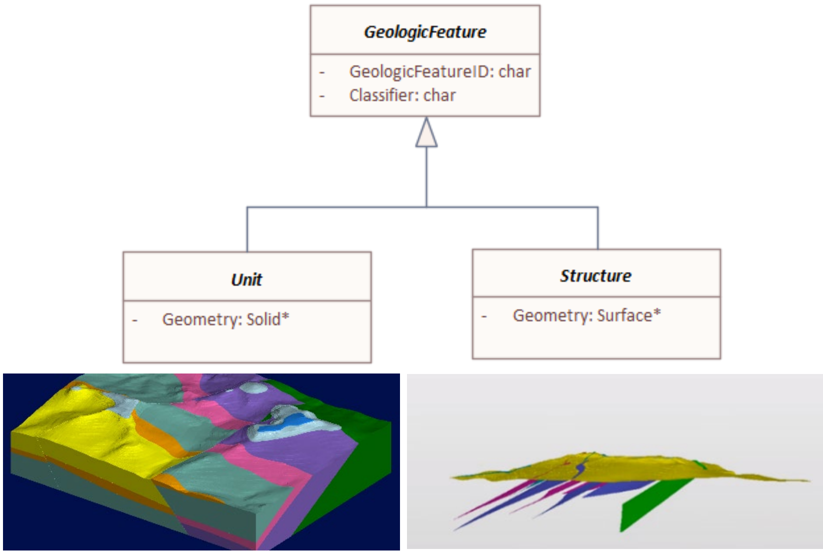


Figure 11. Subdivision of GeologicFeatures into units and structures.

This basic division of geologic features into units and structures into so-called basic types follows the typical logic of geological modelling and is also established as the basic structure in GeoSciML.
In addition to these two basic types, three perspectives are distinguished in the transfer model:

- **Geological** perspective with the classes *GeologicUnit* and *GeologicStructure*
- **Geotechnical** perspective with the classes *GeotechnicUnit* and *GeotechnicStructure*
- **Hydrogeological** perspective with the classes *HydrogeologicUnit* and *HydrogeologicStructure*

This can be used to express the primary technical point of view (perspective) from which a geologic feature is to be defined and interpreted.
In current practice, the majority of information exchanged today is likely to be from the geological perspective. The geotechnical perspective can be chosen alternatively if a specific geotechnical structuring and characterisation of the subsurface is in the foreground. This allows, for example, the subsoil to be subdivided according to purely geotechnical parameters, with the possibility of representing geological subdivisions in a simplified or generalised way.
The choice of perspective has no influence on which properties can be used to describe the GeologicFeature, see also the following explanation of the properties. This means that GeologicFeatures of the geological perspective can also be described with any geotechnical parameters.
The individual perspectives are closely interconnected for technical reasons, so that the definition of a perspective is not always clear (and does not need to be).
The special consideration of the geotechnical perspective in particular was the subject of controversial discussion. Although it has not yet been possible to develop a more in-depth structuring of the geotechnical perspective within the framework of the GEOL_BIM Project, as the corresponding technical requirements have not yet been developed sufficiently, this perspective is introduced as a simple class in the data model. Thus, a semantically dedicated structure is available for primarily geotechnical modelling.
Current international work (e.g. (Simmons, Scott et al., 2022, p. 8), (Beaufils and Halfon, 2022)) is also

moving in the direction of positioning the geotechnical perspective explicitly alongside the purely geological perspective.

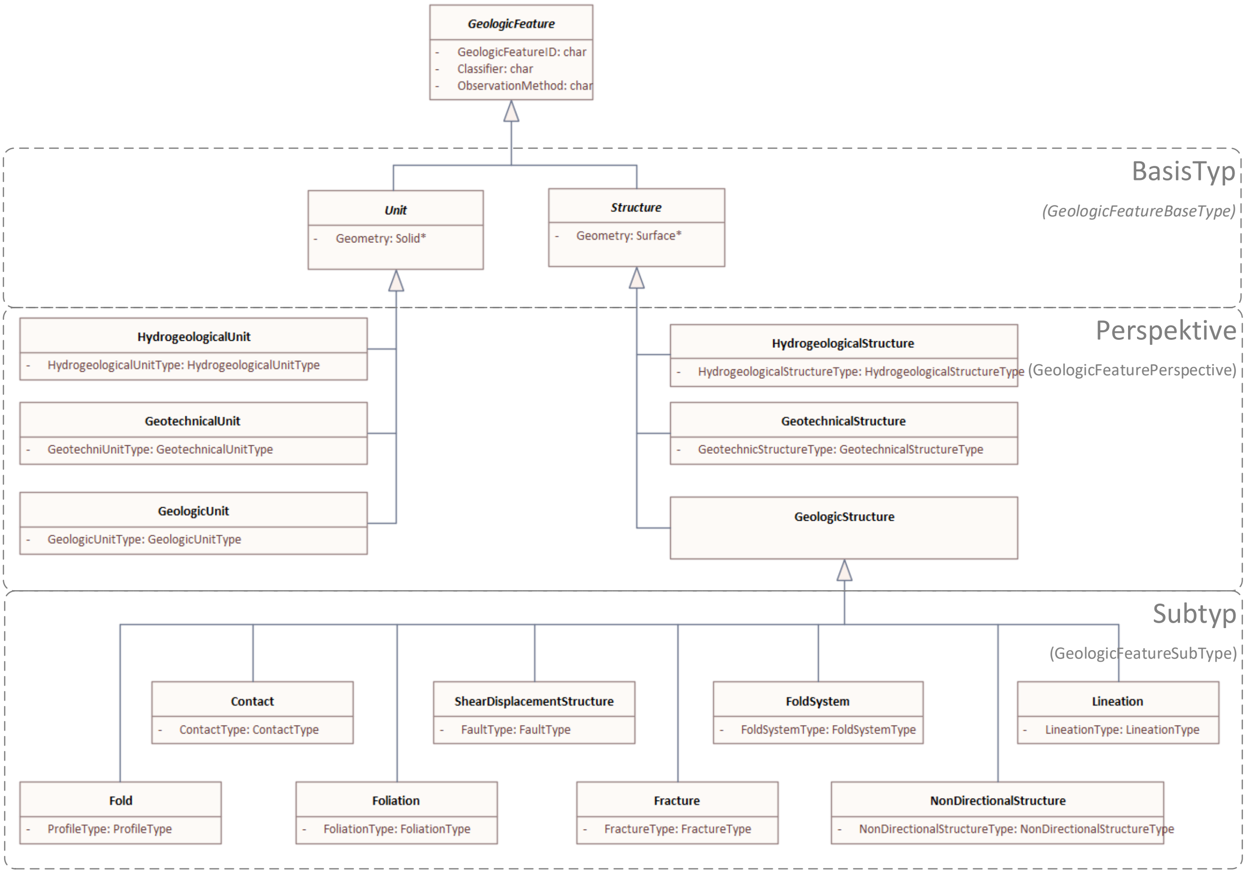


Figure 12. Class diagram transfer model (GeologicFeature sub-model).

The explicit geotechnical perspective with the GeotechnicalUnits and GeotechnicalStructures is an extension to the GeoSciML data model, which was introduced in the GEOL_BIM Project to give specific geotechnical considerations a container. GeotechnicalUnits and GeotechnicalStructures can be used to map explorations or investigations with a primarily geotechnical focus that are not directly based on geological units. However, it should be noted that any geotechnical properties can also be mapped with the geological perspective and that this perspective (with GeologicUnit and GeologicStructure) is therefore also suitable for geotechnical questions (see also the following explanations on the properties).

In the case of geological structures, the data model explicitly distinguishes between different types (specialisations in so-called subtypes) (e.g. Contact, Fold, Foliation, etc.). Please refer to the GeoSciML documentation for a description of the meaning of the individual specialisations of the GeologicStructures.

In the data model, only very few explicit attributes are deliberately defined for the classes. The explicit attributes are generally of a typifying or general nature and hardly define any concrete professional properties. The generic class *Property* is used for the description of technical properties.

The concrete properties of geological objects are usually defined individually for each project and adapted to the respective issues. There are therefore no generally valid properties that can be defined and specified in the same combination for each object type. Therefore, a generic approach is provided in the data model, which in principle allows any *property* to be added to any *GeologicFeature*.

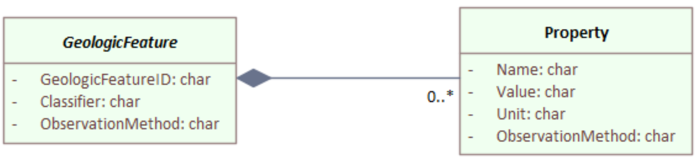


Figure 13. GeologicFeature class diagram detail with property.

While on the one hand, this open, generic approach enables the desired high flexibility for individual adaptations, on the other hand, it has the disadvantage that heterogeneous applications are created, which run counter to the desired harmonisation and interoperability in the exchange of information. For this reason, a catalogue of properties is kept outside the data model, which makes implementation recommendations for the most frequently used properties (standard properties). In this catalogue, the most important properties are defined (method, name, description, units, etc.) and it is also indicated for which object type a property is typically used.

4.1.3.2 Borehole

The classes of the Borehole section can be used to represent geological information in the form of borehole profiles. The class *Borehole* represents boreholes of different types. The borehole must have a line geometry that describes the course of the borehole in 3D.
The borehole profile is formed by intervals (class *Interval*). An *interval* describes a spatial segment along the course of the borehole between a start distance and an end distance. The segment defined by the interval represents a *GeologicFeature* (represented by a "realise" relationship in the class diagram) and thus enables the description of the subsurface with the principles of *GeologicFeatures*.

The intervals are spatially defined by means of linear referencing according to the methods from (ISO 19148, 2012), whereby the line geometry of the borehole represents the referencing axis. With the complete definition of the bore course in 3D and the method of linear referencing, the intervals can also be represented in 3D space. This transformation is carried out automatically via the adapters developed in the GEOL_BIM Project.
With the classes *DrillingDetails* and *CompletionDetails*, more detailed information about the borehole (diameter, drilling method, completion) can be recorded along the course of the *borehole*. With this and the description of various master data on the borehole, there is an equivalent to the swisstopo data model Borehole Data (Brodhag and Oesterling, 2014; Oesterling and Brodhag, 2017).

4.1.3.3 Voxel

The special importance of decomposition procedures for the geometric representation of geological information was shown in the GEOL_BIM fundamental report (Schneider et al., 2021, p. 28, in German). The transfer model therefore has a *voxel* class, which provides a simple structure for representing geological information according to this procedure. A *voxel* represents a *GeologicFeature* (represented by a "realise" relationship in the class diagram) with a cuboid representation and thus enables the description of the subsurface with the principles of *GeologicFeatures*.

4.1.3.4 Observations and measurements

This section allows the mapping of observations (e.g. measurements), independent of the description of a concrete GeologicFeature. Observation values and the associated methods and processes can be described.

4.2 GEOL_BIM IFC sub-model and transformation rules

The geological information of GEOL_BIM is to be exchanged and made available in the context of planning, construction and management projects via the IFC open exchange format. A sub-model (subschema) of IFC is defined for this purpose. This identifies and describes the structures and rules from IFC that are used for exchanging this geological information.

The description of the sub-model is primarily based on version 4.3 of IFC, as this version provides explicit structures for infrastructure structures and in particular for geological and geotechnical topics for the first time. At the time of writing the sub-model (end of 2021), version 4.3 is available as a final draft. It is expected that this version will be finalised and released by buildingSmart in mid-2022 and also published as an ISO standard in 2023 (buildingSmart International, n.d.). The following documentation is based on version IFC4x3_RC4. The separate documentation on the data model (Data Model Results Report) also shows which sub-model of version 4 of IFC can be used to exchange geological information. This version does not yet contain any specific structures for geological information. Therefore, less suitable object types must be used, which are supplemented with corresponding additional conventions.

The following class diagram in Figure 14 shows an overview of the essential entities from IFC (4.3), which are used for mapping the technical content from GEOL_BIM according to the definitions of the GeoSciML+ reference model. The associations between the entities are shown in a simplified way and show the dependencies between the entities that are relevant and defined for GEOL_BIM on a conceptual level (in principle, IFC allows many more and other relationships between the entities).

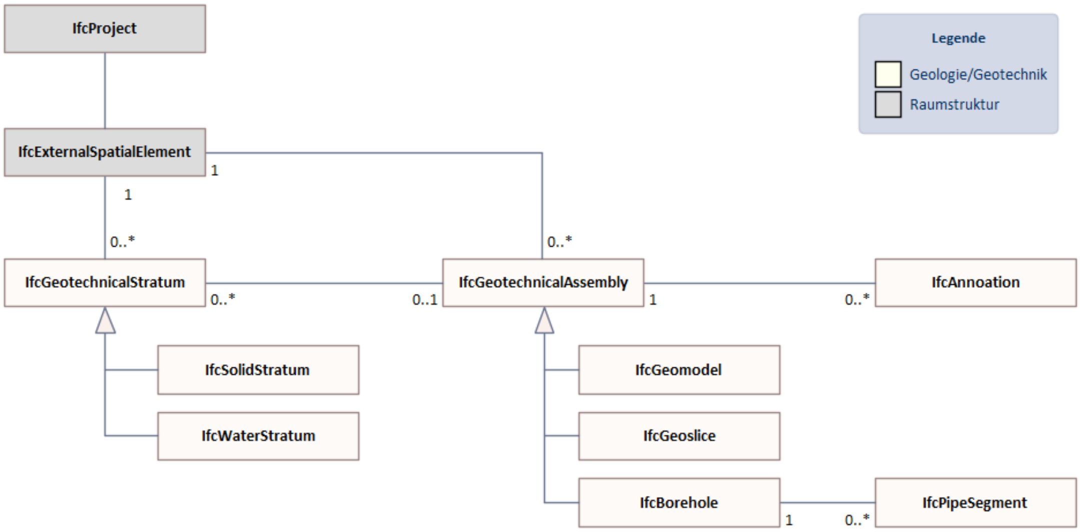


Figure 14. IFC sub-model for GEOL_BIM.

The most important entities are IfcGeotechnicalStratum and IfcGeotechnicalAssembly with their respective child entities. These are the structures newly introduced with IFC 4.3 for mapping geological entities as well as collections of geological-geotechnical information. This is complemented by the use of IfcAnnotation to map observations and measurements that are not directly related to a geological feature.
For the classification into a spatial structure, the entity IfcExternal-SpatialElement is used uniformly for all information.

The following Figure 15 shows the simplified relationship between the transfer model GEOL_BIM and the sub-model of IFC at the level of classes or entities.

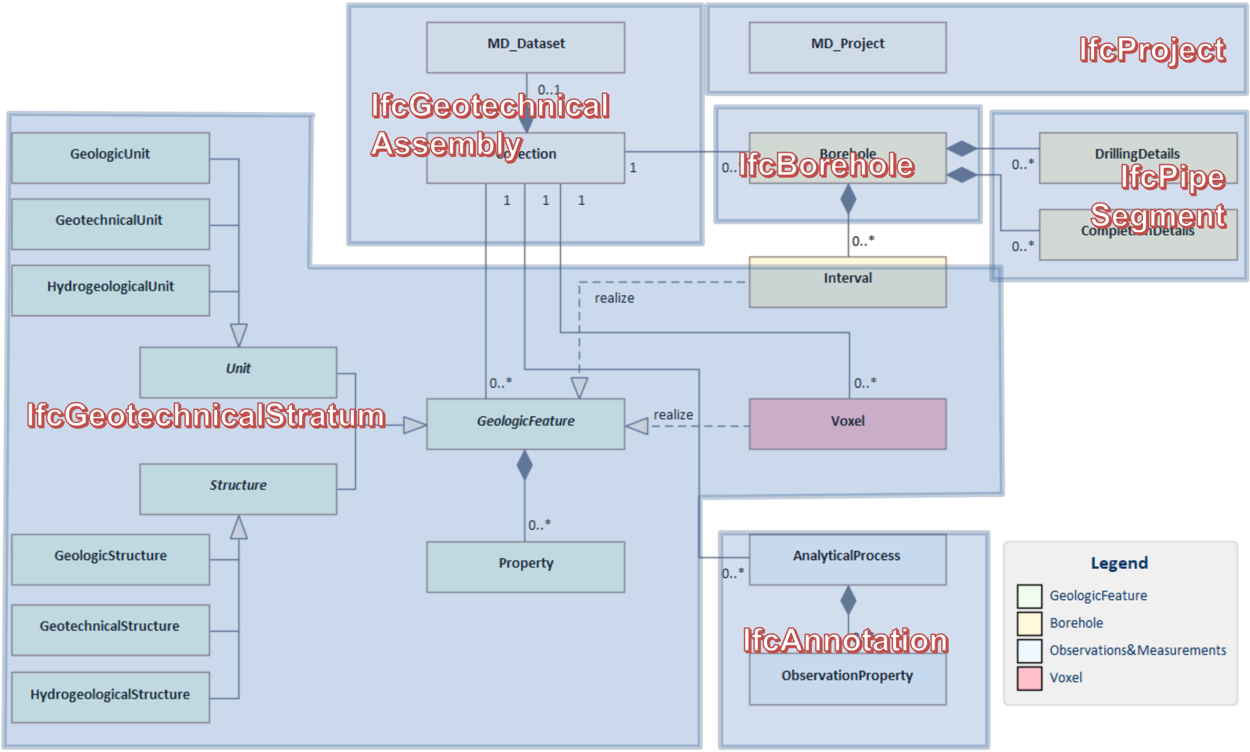


Figure 15. Mapping transfer model GEOL_BIM to IFC (4.3).

In principle, a GeologicFeature is mapped in IFC as **IfcGeotechnicalStratum**. For GEOL_BIM it was decided to map all GeologicFeatures, i.e. particularly also the Structures, as specialisations of IfcGeotechnicalStratum. The different subtypes of a GeologicFeature (GeologicUnit/Structure, GeotechnicalUnit/Structure, HydrogeologicalUnit) are mapped to kindentities of IfcGeotechnicalStratum, whereby these are further differentiated by different ObjectTypes.

In principle, a collection is mapped in IFC as an **IfcGeotechnicalAssembly**. The definition of this "collection class" defined in IFC corresponds semantically to that of the collection.

The mapping of the information on the borehole in IFC is made in two forms. On the one hand, the conceptual-logical information of the borehole is transformed into the assembly IfcBorehole. On the other hand, the more constructional detail information of the DrillingDetails and CompletionDetails is transferred into the component IfcPipeSegment. A user-defined type IfcPipeSegment/BOREHOLESEGMENT is defined for this purpose.

Information from the Observations and Measurements section is mapped in IFC as an **IfcAnnotation**. These are independent observations and measurements, i.e. independent of concrete geologic features. Their definition also contains no reference to building components or spatial structures. They thus fit well into the definition of IfcAnnotation.

The relevant properties of the entities are identified and defined on the second level of the description of the IFC sub-model.

The corresponding attributes and standard properties of IFC were identified based on the attributes in the transfer model or in the GeoSciML+ reference model. If no suitable standard properties are defined in IFC, user-defined properties are added for GEOL_BIM. The property sets specifically defined in the GEOL_BIM Project are designated with a prefix "CHGLG_" (CHGLG as an acronym for CH - Geology). The following diagram shows the PropertySets that are used to map GEOL_BIM in IFC.

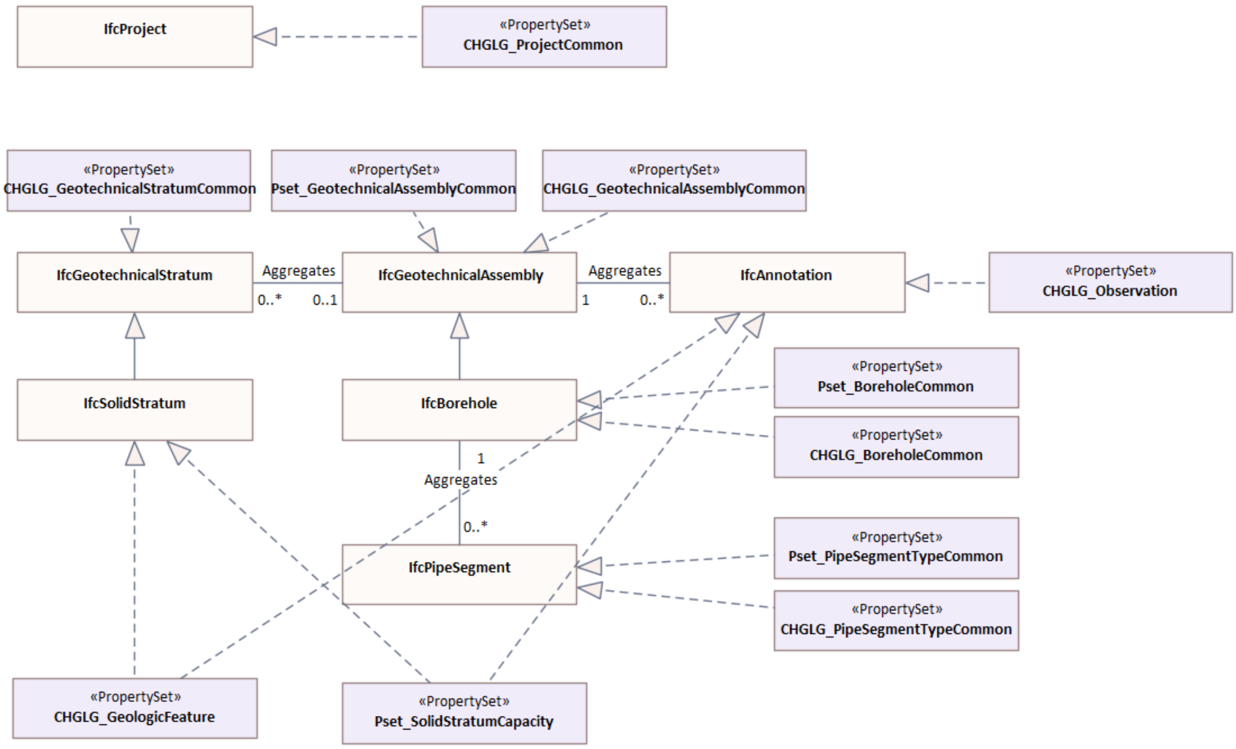


Figure 16. Overview of property groups (PropertySets).

See separate documentation on the data model for a detailed explanation of the transformation rules between the GEOL_BIM and IFC data models.

4.3 Georeferencing

Georeferencing is an essential component that needs to be clarified at the beginning of every project. Georeferencing, however, is not a new topic and existing processes can be partially adopted. Nevertheless, georeferencing takes on new significance with the use of the BIM method and digital building models. The different domain-specific models should be brought together in a coordination model (see also Figure 20). The definition of the reference system and an origin point must be determined for this purpose. If this is not done, coordination in a unified model cannot be implemented, or only with manual adjustments/transformations.

Geodetic reference systems are subject to distortion, which means that inaccuracies can occur as a result of the transformation. If one does not use a geodetic reference system, one is also within the range of distortion for larger linear projects. The type of project is therefore an important indicator for the choice of georeferencing and a possible definition of a change in scale during the transformation (Barmettler et al., 2021).

With the spread of the BIM method from building sector to infrastructure projects, the different worlds of BIM and GIS come into closer contact and the different approaches become visible. The following issues may arise:

- For a more extensive linear infrastructure project (> 4km), the question arises how to transfer a **geodetic reference system** used into IFC.
- How can/must the **length distortion** due to height/projection be taken into account if the planning takes place in national coordinates? Where/how are the resulting quantity adjustments (concrete, ballast, asphalt...) taken into account in the DBM?

- How can a **building construction** project (scale 1:1) **be embedded in an infrastructure project**? What kind of documentation is necessary for this? Up to what extent is such an embedding possible?

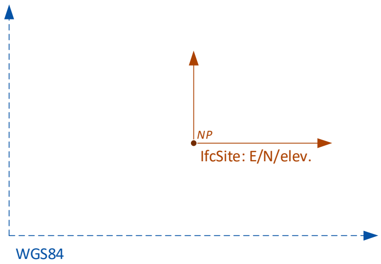
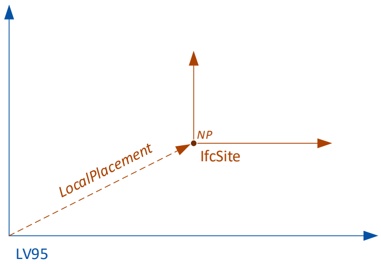
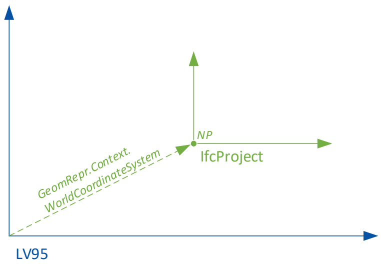
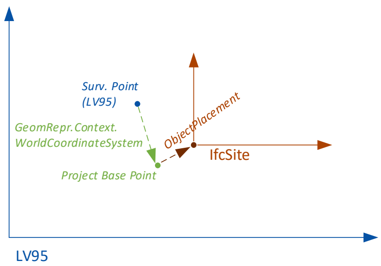
- How do I ensure the **georeferencing** of my DBM, especially when exporting to IFC?

Georeferencing in IFC is described in greater detail in the BIM section of the GEOL_BIM fundamental report, chapter 4.2.1 (in German).

4.3.1 **Level of Georeferencing (LoGeoRef)**

The Centre for Applied Research and Technology e.V. at the HTW Dresden, together with the DD-BIM Competence Centre as a practice partner, has developed a concept that proposes five levels of georeferencing (Kaden et al., 2020). The five levels are divided into simple metrics and define the level of detail of georeferencing. The higher the level, the better the quality of georeferencing. Table 1 describes the five levels and makes an assessment for our GEOL_BIM Project.
The LoGeoRef principle is recommended for the Swiss construction industry in the georeferencing use case guidelines issued by Bauen Digital Schweiz (Barmettler et al., 2021). We have implemented this for our GEOL_BIM interface and the adapters require the corresponding information according to the guidance.
For a fast, easy check of an IFC file and its LoGeoRef level, a simple tool has been developed by the DD-BIM Competence Centre, which can be downloaded for free (Clemen and Görner, 2019).
Downland the verification tool through this link: *https://github.com/dd-bim/IfcGeoRef.*

Table 1. Comparison level of Georeferencing 10 - 50 and assessment for the GEOL_BIM Project.

Level of Georeferencing	Presentation	IFC version	Assessment for GEOL_BIM	Recommendation
LoGeoRef10: Postal address	*"Street, postcode, town, country".*	as of IFC2.3	- Simple and indirect georeferencing - Specification of address in IfcSite or IfcBuilding - Insufficient for geology application	No
LoGeoRef20: Geographical coordinates, point on the mapGeographical coordinates, point on the map		as of IFC2.3	- Simple "point referencing" via a building site attribute as geographic coordinates - Reference to WGS84 - Only an "informative" georeference	No
LoGeoRef30: IFCSite Placemenent		as of IFC2.3	- IfcObjectPlacement of an IfcSpatialStructureElement contains georeferencing - Rotation possible - Not intended as a standard (!) - Suitability for excavations and local projects on a smaller scale	Yes
LoGeoRef40: GeometricRepresentationContext für IfcProject		as of IFC2.3	- IfcGeometricRepresentation context of IfcProject contains georeferencing - Attributes WorldCoordinateSystem, TrueNorth - Suited for excavations and sections in larger infrastructure projects	Yes
LoGeoRef50: IfcMapConversion			- As of IFC4.0 (adaptable in IFC2.3 with PropertySet) - IfcMapConversion defines georeferencing of the "SurveyPoint", including coordinate system parameters - Suited for large-scale and linear project expansions	Yes, as of IFC4.0

4.3.2 Recommendation for geology model

Most geological data in Switzerland is available through the National Survey 95 (LV95) projection. As of IFC version 4.0, EPSG codes can be used with IfcProjectedCRS. The EPSG code 2056 is used for the national coordinate system. With IfcMapConversion the local reference system can be set to an absolute reference. The scale factor can also be used to reduce projection-related distortions. The survey point should be near or in the area of the project. For simplification, the project base point and the survey point can be identical. For projects with IFC 2x3, we recommend georeferencing by project placement.
In any case, the type of georeferencing should be clarified with the project partners so that the data can be imported correctly into the corresponding authoring software.

Local and distortion-free reference systems that are related to a higher-level geodetic reference system (usually LV95) are suitable for customary **building construction** projects. The **LoGeoRef 30 and 40 class** is recommended for such projects.

For infrastructure projects with a **larger geographical scope** (> 4km), it is important to note that different georeferencing systems can be used. For a tunnel project, as described in the application example: 2nd tube Gotthard Road Tunnel (see also chapter 6.1.1), the superordinate routing is to be planned in a global geodetic reference system. The **LoGeoRef 50 class** is recommended for such projects.

Local construction projects, such as tunnel portals, are to be converted in a distortion-free local system. An appropriate transformation of the files can then be carried out using existing control points. The control points to be used must be defined as an information requirement of the client and should also be documented in a BIM project execution plan (BAP) (Barmettler et al., 2021).

4.4 Uncertainties

When people look at maps or plans, they are used to seeing reality depicted there. When we look at a plan or a 3D model, we assume that the transitions that are highlighted in colour also exist in reality. However, in geological mapping and especially in 3D modelling, this is no longer the case. Awareness of uncertainty must be raised. Uncertainties can be indicated in plans with dashed lines, question marks, uncertainty corridors or even increasing fuzziness. But how is this done in 3D models and how is this information communicated in IFC? After an extensive literature review and discussions with the advisory group, two approaches were pursued. The description of uncertainty using attributes and the description of uncertainty geometrically (see also chapter 3.4). In both approaches, the evaluation of the additional information in the corresponding BIM viewers also played a major role. For this purpose, an analysis was carried out with 7 widely used BIM viewers.

3.4.1 Attributive description

Various possibilities for the visualisation of quantified uncertainties arise depending on the overall data processing (data, methods, algorithms, etc.). Each element of a service provided by a geologist can be assigned a result value or a distribution, regardless of whether it is a geometric object, a support or node point or a map polygon. This result value can be assigned a confidence interval, a range (minimum to maximum value) or a probability.

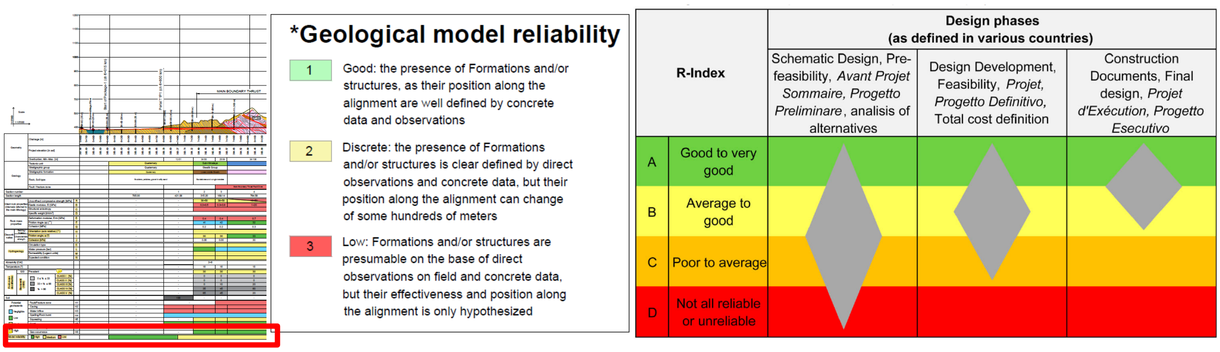


Figure 17. Probabilities in the geological model across the design and planning phases. Representation of a probability of the geological model using the example of a geological profile incl. tunnel belt according to SIA199 (left source Lombardi AG) and probability calculation of the R-index (right) (Dematteis and Soldo, 2015).

The corresponding values (or bandwidths/min. max. values) can be mapped in additional attributes. The additional attribute values can then be evaluated accordingly or displayed visually in addition to the element.

The quantification of uncertainty by means of attributes can be accomplished in very different ways. The most widespread values are briefly explained in Table 2.

Table 2. Compilations of possible values for quantifying uncertainty.

Value	**Description**
Result value	Numerical value, e.g. measurement result
Mean value	Arithmetic mean
Standard deviation	One, two or three sigmas
Median	Median
Percentiles	5%, 25%, 75% and 95%
Relative probabilities	Numerical values from 0 to 1
Quality markers	Good, sufficient, doubtful
Quality description	Text field for more detailed description

4.4.1 Geometric description

Another way to visualise the uncertainty in a 3D model is to define an independent 3D geometry that represents it. In addition to the effective geometry, a second, or even several, geometries are recorded for the object, which encompass the entire space covered by the inaccuracy. Thus, in addition to visualisation, spatial analyses can also be used to detect potential spatial conflicts. In the GEOL_BIM Project, there are no practical examples with spatial geometries that could be represented as additional "imprecision geometries" in a digital building model. Therefore, this approach is implemented with a synthetic example (see Figure 18).

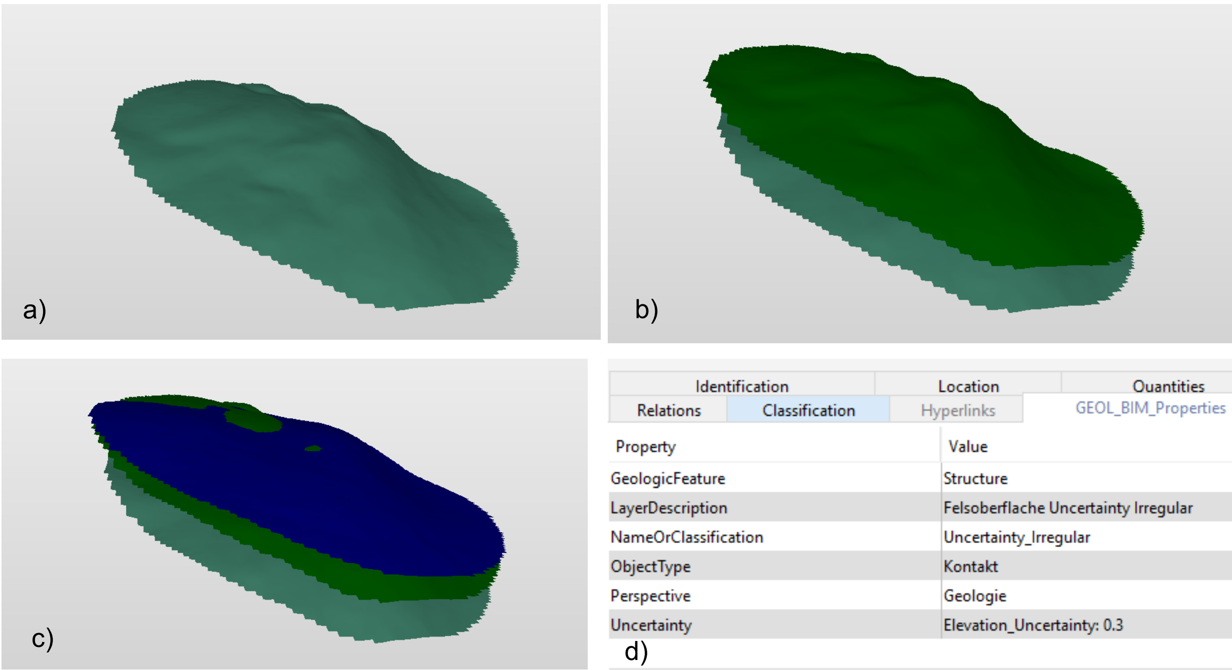


Figure 18. Representation of the "uncertainty geometry" in the Solibri Office BIM viewer: a) the actual rock surface b) additional area of uncertainty with a fixed distance to the rock surface c) additional representation of an uncertainty geometry using an uncertainty index d) representation of the properties using the GEOL_BIM PropertySet.

5 GEOL_BIM interface

One goal of GEOL_BIM is to achieve significant improvement in data exchange quality and time-saving at the interfaces between the corresponding experts (e.g. geology/geotechnics and civil engineering) through suitable extensions and adapters. During the interview phase of GEOL_BIM, a focus was placed on the processes used and the software products used in the offices of the advisory group. Based on this information, an attempt was made in the workshops to define a common understanding of the processes for data exchange. Along with the diversity in the projects (of the people involved in the workshop), a different understanding of the task area also represented a challenge. The distinction between the disciplines of geology and geotechnics could not be conclusively clarified. In certain offices, the activities are clearly separated here, while in other offices there is no separation between these two specialist disciplines. To simplify matters, Figure 19 shows these two roles in one line. However, it is also possible that these roles are distinguished and the description of the subsurface (geology) and the assessment of the subsurface (geotechnics) are made by different parties. The exchange with geotechnics plays an important role in the creation of the geology model and the refinement of the model is driven in an iterative process. A close exchange with the specialist model of civil engineering is necessary for the creation of a subsoil mode. The process for creating the subsoil model[2] is described as iterative in the projects. The collaboration is to be intensified thanks to a better interface. The GEOL_BIM interface is necessary for conducting the data exchange in a more standardised manner.

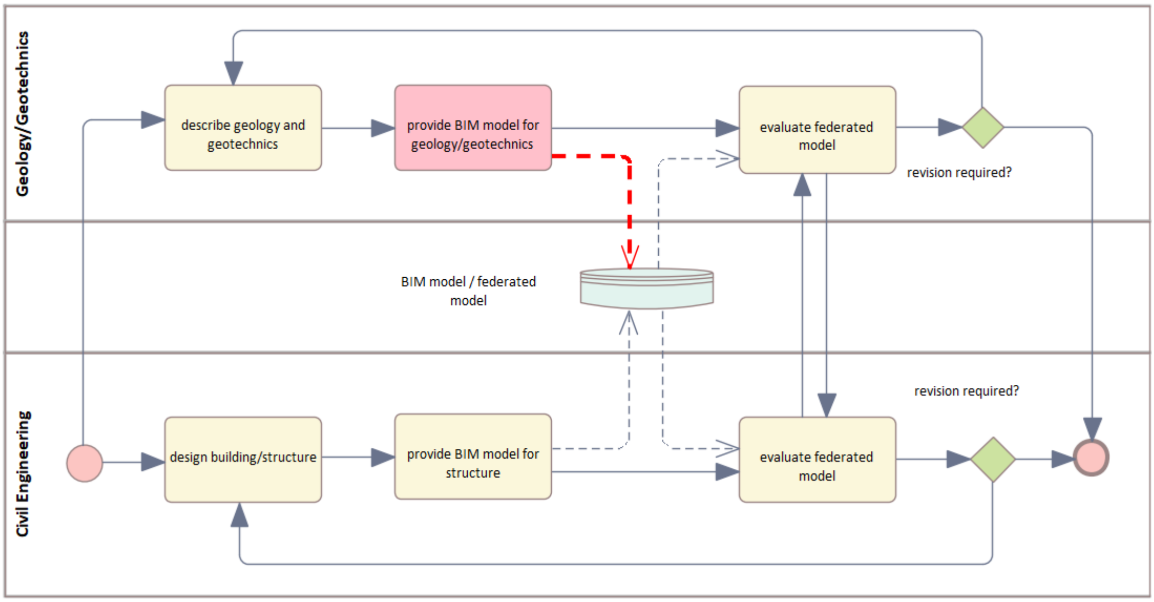


Figure 19. Simplified process illustration for the "creation of a building site model".

Based on the feedback from the monitoring group members, widely used data formats for the geometric representation and for the descriptive geological[3] information will be predefined as structured input data. The corresponding input data will then be converted into IFC format through a web application for exchange with the specialists in BIM-based construction projects. The focus here is on a section of the geological information and not on completeness from the geologist's point of view. Geological information is recorded and processed by geologists in various specialised software products.

[2] Geotechnical model extended with the actual structure. The subsoil model is not an independent specialist model, but is already a combined model (geotechnical & civil engineering model).

[3] In the report, the term geological information stands for geology and geotechnics respectively.

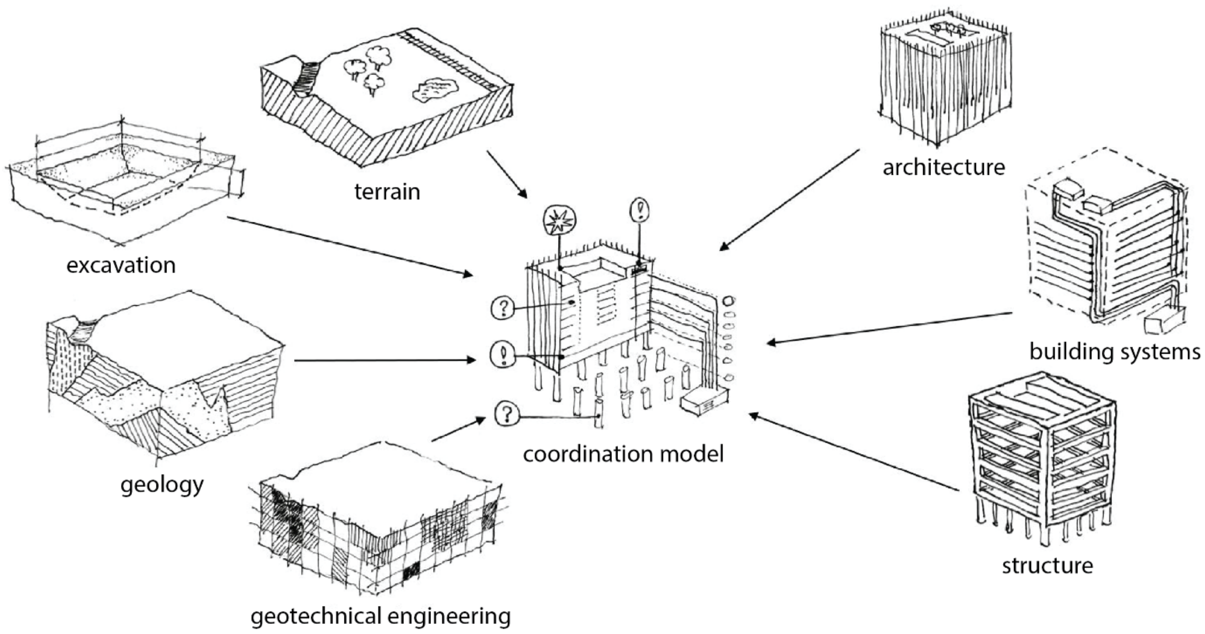


Figure 20. Coordination model with the different domain-specific models.

The coordination model in Figure 20 is intended purely as an information base (i.e. only the data, no application for its processing/presentation/analysis). A conceptual data model is developed and described for the digital building model (geology model), which is described in chapter 4.1.1.

Definition terms:

Geological model	Describes the structure of the subsurface, the composition of rocks and the cavities formed within them. Geological models serve the purpose of illustrating and comprehensively communicating complex geological relationships. Hydrogeological models extend geological models by the liquid component water.
Domain model geology	Part of the geological model that is transferred as information to the construction project/coordination model.
Geotechnical model	A geotechnical model is created on the basis of a simplified geological model by enriching it with the technical properties of the subsurface. Geotechnical models serve the purpose of assessing the suitability of the subsurface for construction activities.
Domain model geotechnical engineering	Part of the geotechnical model that is transferred as information to the construction project/coordination model.

5.1 Adapter

Three adapters have been developed for the GEOL_BIM Project (bhl2ifc, vxl2ifc and gf2ifc) as standalone tools using the Python programming language. The adapters were developed taking into account the different demands of the monitoring group. They were developed quite generically and can therefore be used in a wide range of different projects, offering great flexibility. However, this is not very effective in terms of the desired harmonisation in data exchange. Data preparation from the special software is still a very time-consuming step in some cases.

An overview of which input formats are needed for which adapters can be seen in Table 3. A detailed description of the file formats is provided in the following chapters and in the appendix.

Table 3. Overview of the input formats for the various adapters.

		bhl2ifc	vxl2ifc	gf2ifc
Configuration & metadata	Information about description of the data and the origin of the coordinates. Further properties for transformation of the data.	*.xlsxl	*.xlsx	*.xlsx
Geological, geotechnical properties	Properties that are of interest for the geology/geotechnical engineering model in the case of a common coordination model.	*.xlsx	*.xlsx	*.xlsx
Geometries	Information on the geometric representation of the data (points, lines, areas and volumes).	*.xlsx (*.ags examined)	*.csv *.xlsx	*.dxf *.obj *.stl *.ts

5.1.1 Bore profile (bhl2ifc)

Link to source code	https://gitlab.com/CHGEOL/geol_bim-bhl2ifc
Link to EXCEL template	https://gitlab.com/CHGEOL/geol_bim-bhl2ifc/-/tree/main/data/input

Soundings, excavator slots and other line-shaped information can be transformed with the adapter for borehole profile. In addition to classical bore profiles, a tunnel profile was also created along the tunnel axis in the practical example of the 2nd tube of the Gotthard Road Tunnel (see also Chapter 6.1.1) with the corresponding information according to the SIA 199 definition. The geometrical elements created are displayed as cylinders along a curved borehole axis.

The adapter for borehole profile requires an EXCEL file as input format. Also investigated was whether the international *.ags format can be used as additional input. However, this was not implemented as an option for additional input formats.

The EXCEL template is structured as follows:

Table 4. Description of the transfer template for borehole information.

Register sheet	Description
Metadata	Information on the data description and origin of the coordinates.
Borehole	General description of one or more boreholes (ID, name and date). Indication of the centre point of the drill starting point.
Geometry_straight_borehole	This tab sheet must be used for straight boreholes. Enter the start and end point of the borehole in absolute coordinates. Each borehole is described with two points.
Geometry_Curved_Borehole	Use this tab sheet for curved boreholes. Input of several support points in absolute coordinates of a curved borehole.
Interval	In this tab sheet the borehole information should be defined for each interval. In addition to the geometric information of the depth in the borehole, an object type definition must also be made. Here you have the choice of the values GeologicFeature, Perspective and ObjectType described in the data model. Subsequently, the attribute list should be extended and adapted according to the needs of the projects.
Example_Interval	Example for the Interval tab
Survey Points	Projekt Base Point and Survey Points for localising the project.

5.1.2 Voxel (vxl2ifc)

Link source code	https://gitlab.com/CHGEOL/geol_bim-vxl2ifc
Link EXCEL template	https://gitlab.com/CHGEOL/geol_bim-vxl2ifc/-/tree/main/data/input

Space-oriented voxel models can be transformed to IFC with the adapter for voxels. The actual voxel geometry is defined with the respective centre coordinate. The dimension of the voxel can be defined for each coordinate axis. This makes everything possible, from cube geometries to cuboid objects. The orientation of the voxels can also be defined, with dimension and orientation defined once for each transformed file.

User-defined properties can be defined arbitrarily in the CSV file. Transformed in the application examples were geological and geotechnical properties as well as uncertainty properties.

5.1.3 Interface and envelope (gf2ifc)

Link source code	https://gitlab.com/CHGEOL/geol_bim-gf2ifc
Link EXCEL template	https://gitlab.com/CHGEOL/geol_bim-gf2ifc/-/tree/main/data/input

The adapter for GeologicFeature can be used to transform interfaces and envelopes to IFC. The interfaces and envelopes must be of the triangular mesh type and in one of the formats described in Table 3. In addition to the *.xlsx file, other geometry files are used with this adapter. The reference and the use of the files are specified directly in EXCEL.

The gf2ifc adapter can also be used for geological profile sections. However, the data must be processed beforehand for this purpose. A workflow was developed in GEOL_BIM using FME for pre-processing of the data, which is described in chapter 5.1.3.1.

The EXCEL template is structured as follows:

Table 5. Description of the transfer template for interfaces and envelopes.

Register sheet	**Description**
Metadata	Information about the data description and origin of the coordinates.
GeologicFeatures	The geometric information and descriptive attributes are linked in this tab sheet. One object type is assigned per line. Ultimately, the attribute list is to be extended and adapted according to the needs of the projects.
GeologicFeatures example	Example of a fictitious project with the 12 most important attributes for a geologic unit.

So-called *GeologicFeatures* are used to describe the subsurface. The description and a definition can be found in chapter 4.1.3.1.

5.1.3.1 Preliminary process for geological profile sections (FME)

What is a geological profile?
Geological profiles are cross-sections of the geological subsurface oriented orthogonally to the mean earth surface along a line (profile trace). Profile traces can be straight or curved lines between two end points. Alternatively, profile traces can also be divided into segments at predefined inflection points, which are also either straight or curved. For tunnel design, the description of the rock mass is strictly separated from its assessment. The result separates the descriptive cross-section through the geology of the rock mass from the technical properties of the subsoil and their assessment, which are represented in the form of a tunnel band under the profile.

Why
Although the profiles are mostly in 2D, they are considered important basic geological information and are often used to illustrate the geological subsurface. An integration into the BIM environment is therefore worth considering.

How
As described in the previous section (section 5.1.3), triangle meshed surfaces can be transferred to IFC using the GEOL_BIM interface. Some geological 3D expert software allows the creation of profiles in 3D, mostly in the form of polygons. For the GEOL_BIM interface to work, these polygons need to be converted into triangular meshes (which most expert software can do) and then exported to either .dxf or .obj format.
In many cases, however, the profiles are vectorised 2D drawings. In the next part, a solution is presented with which these vectorised 2D profiles can be converted into three-dimensional triangular meshing surfaces and then transferred to an IFC file (see also Figure 21).

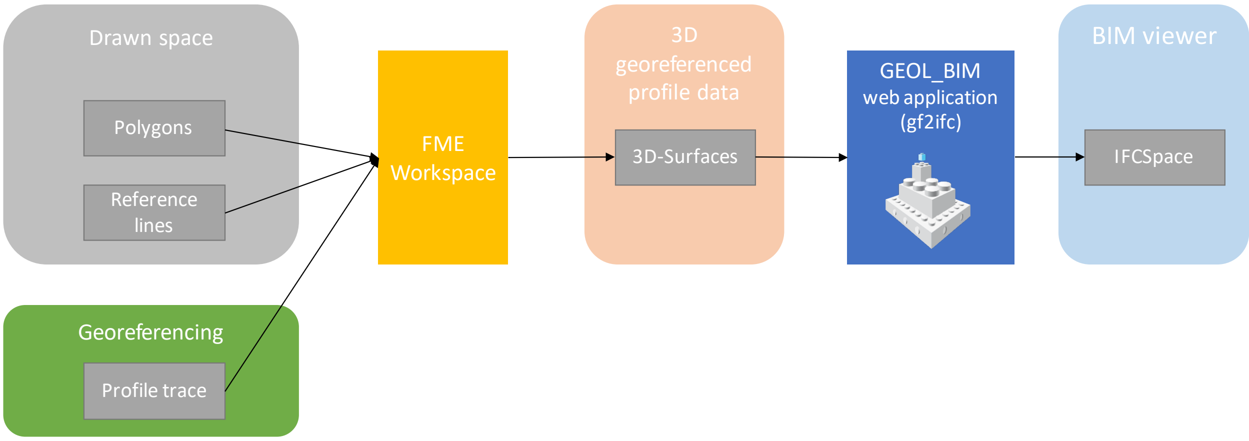


Figure 21. Workflow for pre-processing 2D geological profiles. Shown is the conversion of non-georeferenced 2D profiles into 3D georeferenced profiles with subsequent transformation to IFC.

Attribution
The necessary attribution of the 2D vectorised profiles consists of a unique identifier for each polygon and profile. Attribute is possible with software that allows the attribution of 2D vector data and corresponding export formats (e.g. ESRI ArcMap or Adobe Illustrator with the MapPublisher add-on) or using an external Excel spreadsheet that references the geometry file by name, similar to the gf2ifc adapter.
It should be noted that the ability to georeference is not required at this point.

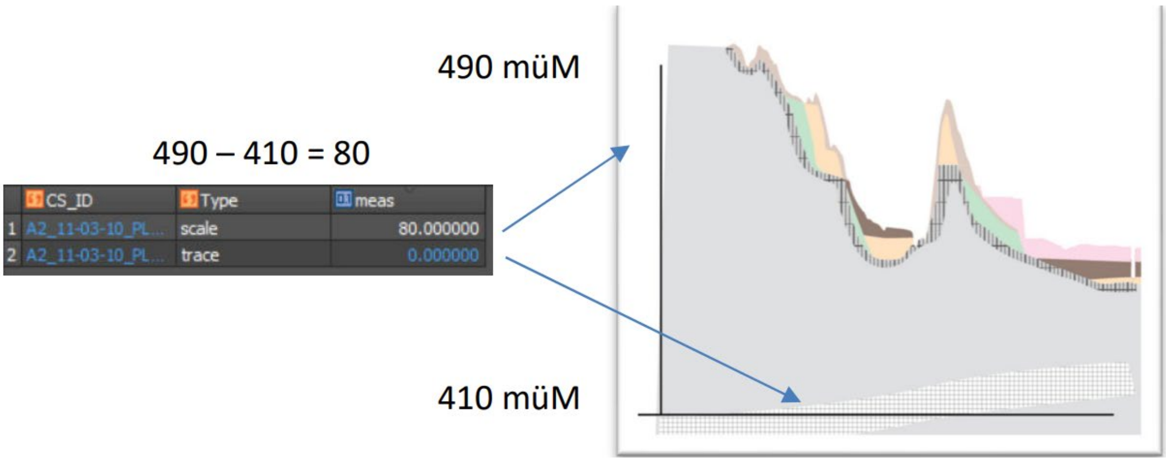


Figure 22. Definition of additional reference lines in the profile.

Reference lines
Additional reference lines must be defined within the vectorised drawing (see also Figure 22). They will be used later to scale the vertical and horizontal dimensions of the profile. Essential attributes besides the profile ID ("CS-ID") are the type ("Type") of the two reference lines and specification of the length value of the vertical reference line ("meas").

Georeferencing
To locate the profile geographically, it must be linked to a georeferenced 2D profile trace. If this 2D profile track does not yet exist, it must be created in a GIS-like environment (see also Figure 23). The length of this profile track corresponds to the length of the horizontal reference line. Essential attributes are the profile ID ("CS_ID"), the elevation of the profile track ("Elevation", corresponds to the height of the horizontal reference line in metres) and the attribute "leftDir". The latter indicates the compass direction (e.g. NE or NW) in which the left end of the profile track is aligned.

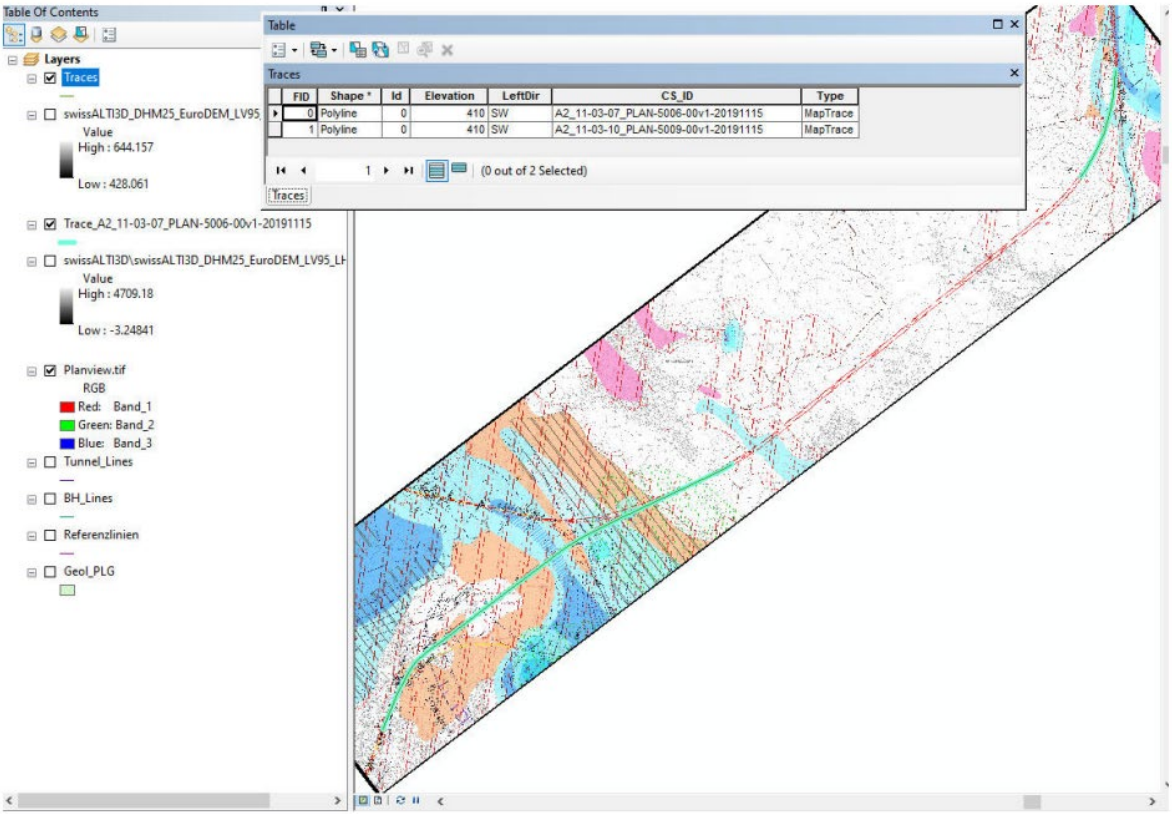


Figure 23. Georeferencing of the profile trace in a GIS-like environment.

By combining the reference line and the profile trace, the profile polygons can now be correctly positioned, aligned and scaled in 3D space using the "3DcrossSectionGenerator" script in the FME software. The result is shown in Figure 24.

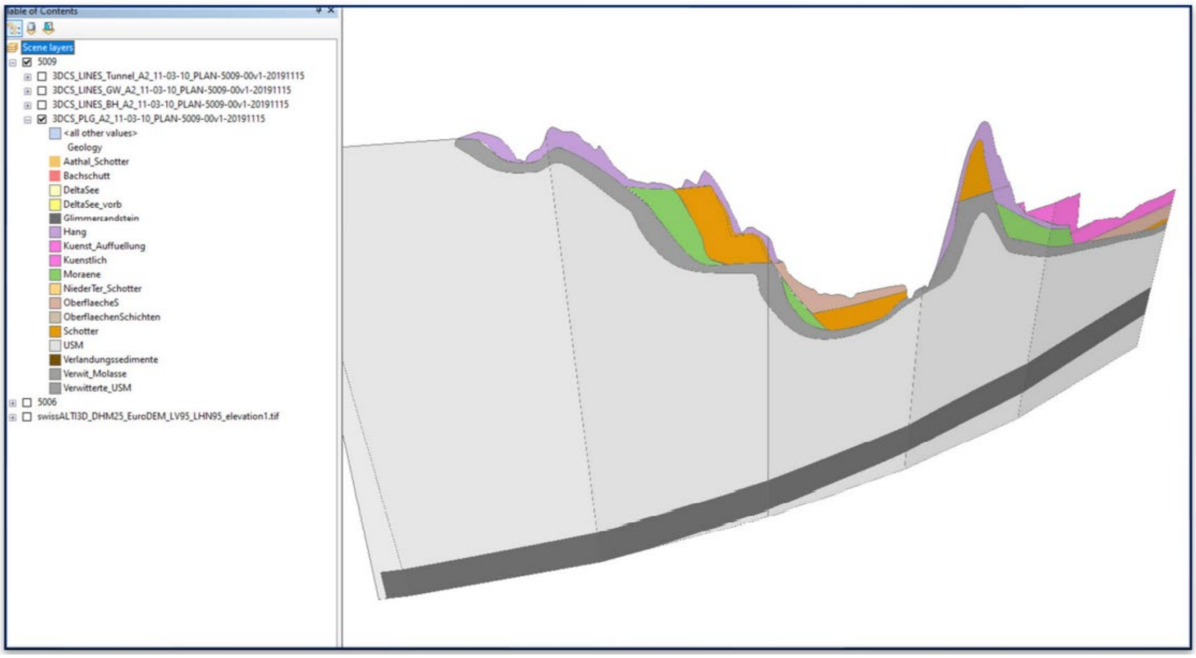


Figure 24. Result of the FME conversion in the form of a 3D georeferenced profile.

The polygons can be subsequently converted into triangular mesh surfaces and exported as .dxf or .obj. By using the gf2ifc transformer, the profile can then be converted into an IFC file, which can be loaded, visualised and analysed in a BIM viewer (see also Figure 25).

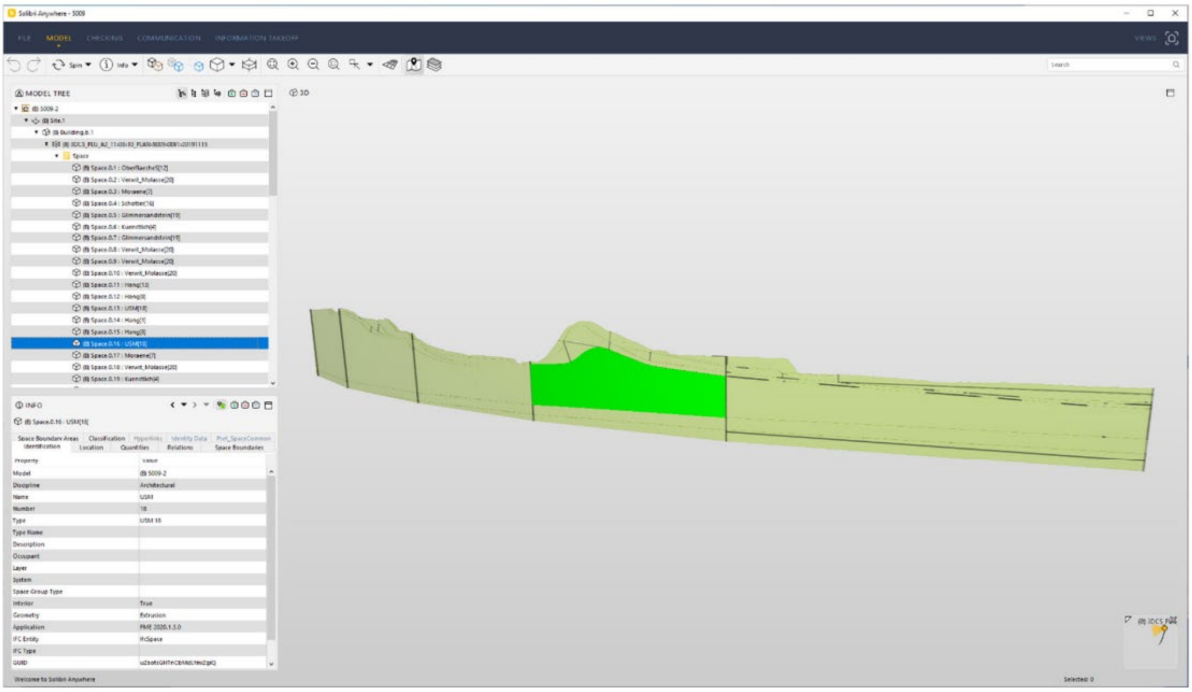


Figure 25. Visualisation of the 3D geo-referenced profile in a BIM viewer.

5.2 Web application

5.2.1 Initial situation

In the course of the GEOL_BIM Project, three command line tools were developed in the Python programming language to match the three adapters vxl2ifc, bhl2ifc and gf2ifc.
Handling of the command line tools, especially for the installation and less during operation, has turned out to be a technological hurdle in practice, in consideration of user competences.

From the experience with the command line tools, it was concluded in the GEOL_BIM Project that the technical functions of the three adapters must be more easily accessible for the user. With the decision to implement the adapters as a web application, accessibility and thus the use of the GEOL_BIM interface should be increased, offering the following advantages:

- No installation (on different platforms) necessary.
- Guaranteed, centralised software maintenance and servicing (updates, patches, etc.).
- The software is operated via a graphical user interface in the browser.

This meant that in addition to the technical challenges in the GEOL_BIM Project, a solution was needed for the development of a graphical user interface (GUI).

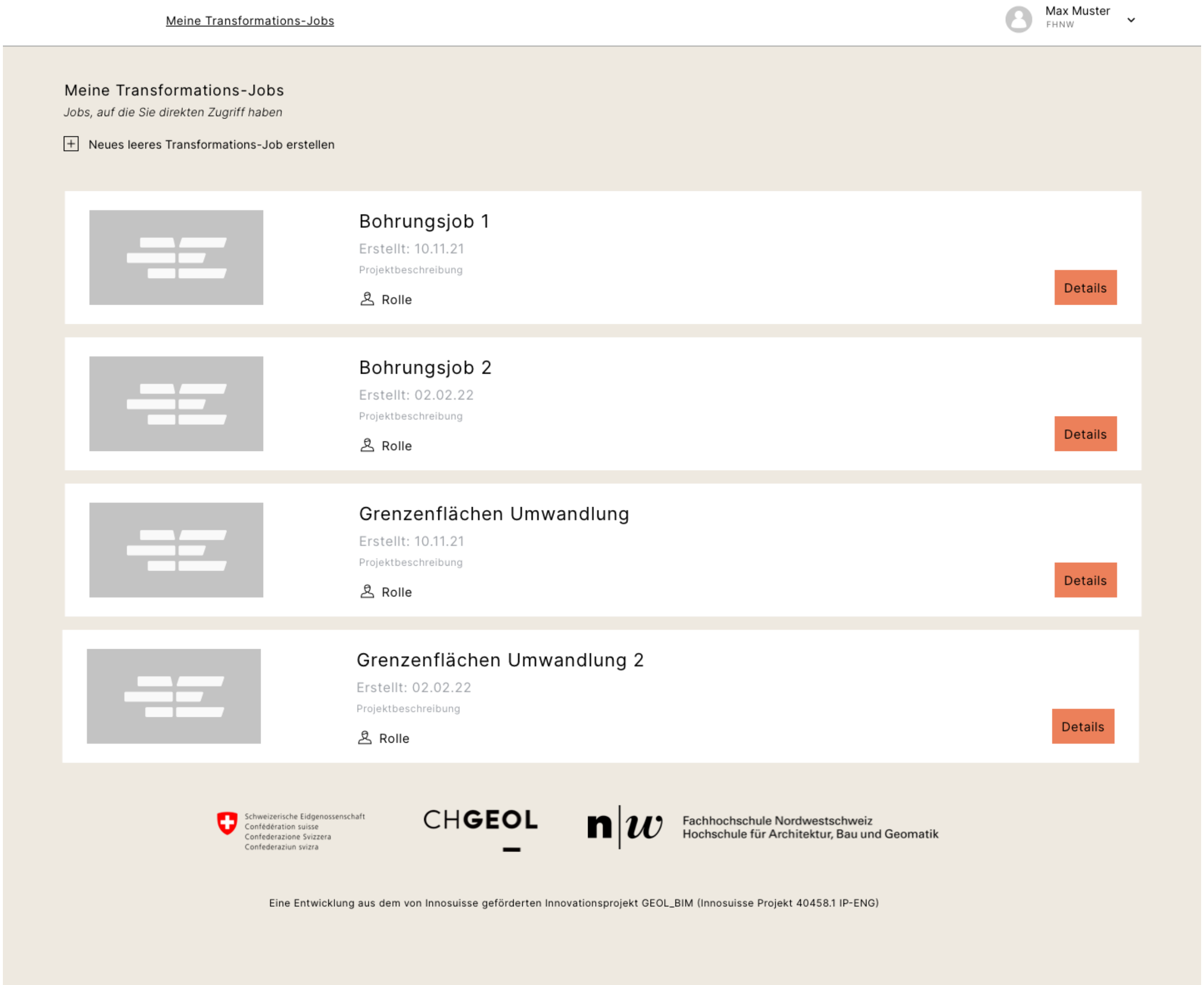


Figure 26. Start page of the GEOL_BIM web application prototype.

5.2.2 Requirements for the web application

The web application user is assumed to be a geologist or a professional with a background in geology. It is therefore clear that its primary task is to convert the user's technical data into an IFC file as quickly as possible, in simple and few steps. The geologist's data is either entered manually in Excel or comes from automated extracts from common geology software applications.
The geologist uses the application either in time units or sessions. These are reflected in the application itself, or in its GUI, and represented as "transformation jobs", hereafter called jobs for short.
In addition to the primary task, the project team identified the following additional use cases of a requirement nature during the specification phase of the web application:

- The user has an overview of current and past jobs in the application.
- For the training area, the user creates sample cases and repeatable tutorials with the application.
- The application includes a descriptive and interactive user manual.

Errors in the data or the operation of the application are also to be presented in detail and in a comprehensible manner and visually as close as possible to the graphical representation of the cause.
Because all of these use cases have a strong tutorial character, they are subsequently also summarised under the term tutorial.
One of the jobs of the web application is therefore:

- Convert technical data into an IFC file as quickly as possible.
- Tutorial for training or further education.

The project team therefore had to choose a form for the detailed graphical representation of a job in the GUI that would serve both purposes.

5.2.3 Basic idea of the GUI

Depending on the adapter, a different type and number of files are required for the conversion into an IFC file.
The basic idea of the GUI is that a block is created in a job for each data source and that the entirety of the blocks results in exactly one IFC file after the conversion is triggered.
For example, a job contains a series of blocks. The first block represents the configuration in the form of an Excel file. The second block then also contains the detailed data. In both blocks, the user uploads files to the web application. After triggering the conversion, the user downloads the IFC file from the job and opens it in the application of his choice.
For a tutorial, however, a job can also be designed like a worksheet. In addition to blocks with input data, the user enriches the job with blocks with titles or section texts. The order of the blocks in a job becomes important and, in addition to the actual result IFC file, content comes more to the fore. The blocks with input data are optionally prefilled, depending on whether the job has the character of an online tutorial or an exercise.

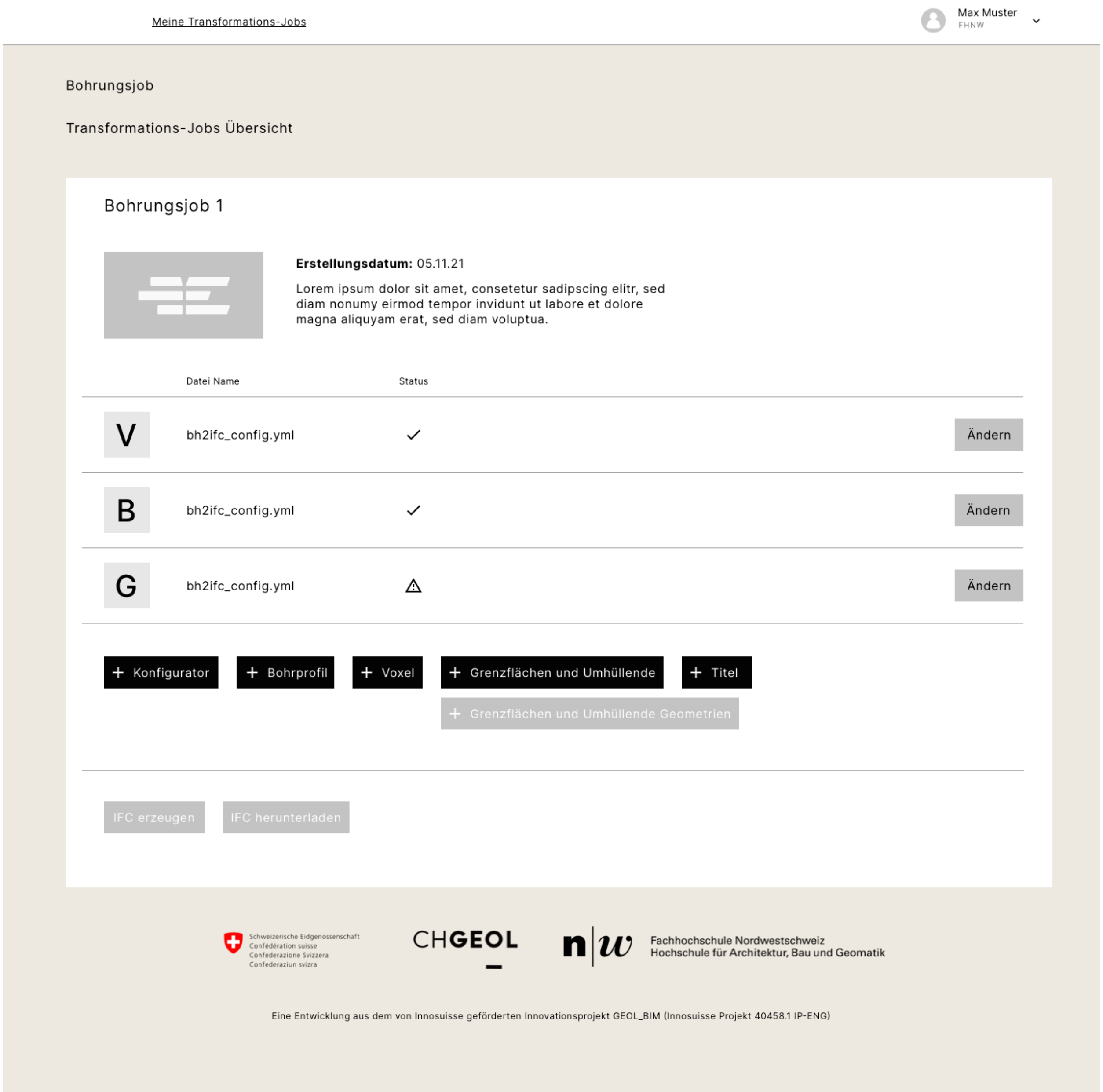


Figure 27. Web application job overview and the display of blocks (prototype).

GUI web application: Add bore and a XLS then appears automatically.

5.2.4 Specifications for the web application

The project team had to refine the requirements for the web application very early in the corresponding project phase, also formulate application exclusions, and transfer all this into a concept.

- The web application is a prototype and not a final system. It runs efficiently for research purposes and can be converted into a contemporary professional operation without much effort.
- The web application applies either the vxl2ifc, bhl2ifc or gf2ifc adapter during conversion.
- The application does not carry out any coordinate transformation. There is only one coordinate system per job, which applies to all data of the blocks and the resulting IFC file.
- The web application is not an IFC editor. IFC data is not read in, but generated.
- Picking up on the two previous points, the web application does not include functionality to merge multiple IFC files or those with possibly different coordinate systems.

- Visualisation of the resulting IFC file is up to the user.

5.2.5 Choice of technology

The choice was made for modern architecture with Python, because it best meets the requirements of continuity and maintainability.
Python must be specifically retained, because both the custom in software development in academia and the resources in software development in business and the situation on the labour market speak in favour of this choice.
This choice was made contrary to the requirement not to store customer data on the server. On the other hand, consistent authentication by means of logins and a comprehensive authorisation mechanism in the web application help to comply with data protection guidelines. The server-centred approach also helps to meet the tutorial use case with the access calculations.

5.2.6 Conception

The project team formulated the technical specifications with the aim of creating optimal conditions for the external continuation and maintainability of the web application.

- The software components used are modern and the architecture corresponds to the current state of the art.
- The operational structure of the software is placed in Docker containers.
- The responsibilities are neatly separated into: database, backend and frontend.
- PostgreSQL is used as the database, a proven and robust representative of a classic relational SQL database.
- The business logic in the backend is formulated in Python programming language.
- The backend is implemented as a REST API in Python.
- Templating takes place exclusively in the frontend with Vue.js. Templating means the transfer and representation of domain-oriented objects, such as a job or a block, into a representation in the application`s GUI.

The web application is expandable for professional operation and must therefore be expandable to meet high performance and security requirements.

6 Case studies

6.1 Applications in tunnelling and subsoil

6.1.1 SIA 199 using the example of the second tube of the Gotthard road tunnel

6.1.1.1 Initial situation

A second tube of the Gotthard road tunnel is currently being planned for the Swiss national roads. From the previous project phases, fundamental geological and geotechnical data are available from the general project (GP), the implementation project (AP) and the detailed project (DP) of the Federal Roads Office FEDRO. In addition to geological maps and profiles of the region, longitudinal and horizontal geological profiles are available along the tunnel axis.

When creating these profiles, "Erfassen des Gebirges im Untertagebau" (Capturing the rock mass in underground mining) according to SN 531199:2015 (SN531199:2015; SIA 199, 2015) is of central importance. The geological, hydrogeological and geotechnical description, in combination with experience from structures in comparable rock masses (Section 4.13), serves to assess the rock mass with regard to "its behaviour in the creation of the cavity, its degradability, the water and gas influences and the utilisation of the excavated material (Section 4.21)" [Translation of the German wording]. The assessment of the rock mass is the basis for planning measures to control existing hazards. To this end, the regulations require a clear presentation of the reliability of the geological, hydrogeological and geotechnical descriptions and their possible deviations. The standard is known for its tabulated descriptions of rock properties, which are typically presented under a geological cross section through a mountain range along the tunnel axis.

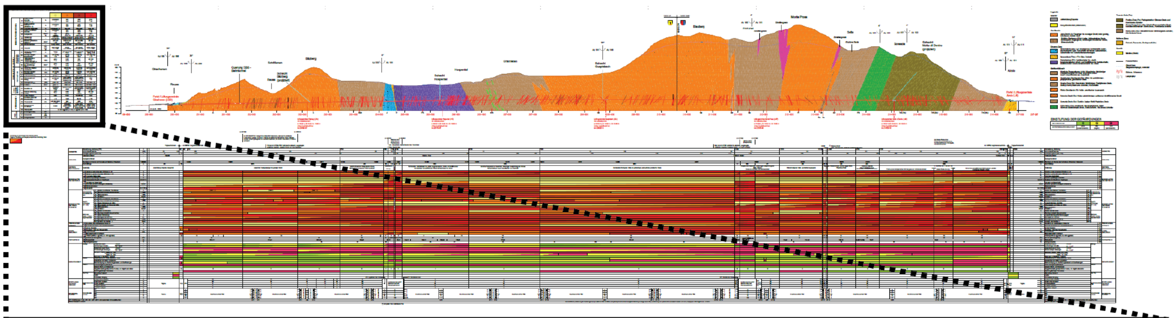
For the present case study, Lombardi AG developed a proposal for the communication of SIA 199-compliant descriptions of the rock mass via digital building models when using the BIM method.

6.1.1.2 Procedure

According to the conventional procedures to date, the description of the rock properties is done outside the 3D modelling software, as the automatic generation of SIA 199-compliant representations is mostly not supported. In this specific project, the creation of SIA 199-compliant tables was partially automated by using a workflow developed by Lombardi AG in the Python programming language to transfer the geological, hydrogeological and geotechnical descriptions compiled in Microsoft Excel into an SIA 199-compliant table. According to this conventional approach, the resulting table is merged with a geological cross section – generated manually or from 3D modelling software.

Based on the most up-to-date geological maps and longitudinal and horizontal profiles of the detailed project at the time of conducting this case study, a geological 3D model was developed along the planned second tunnel tube. Since the longitudinal profiles used were already available in SIA 199-compliant form (Figure 28), the case study focuses primarily on their representation in the three-dimensional digital building model. The modelled geometries were exported from the geological 3D software Leapfrog Works into the open OBJ format. Using the transformers developed in GEOL_BIM, the exported geometries were attributed with the geological, hydrogeological and geotechnical descriptions compiled in Microsoft Excel and converted into the open data exchange format IFC.

A.



B.

					①	②	③	④
EIGENSCHAFTEN DES GESTEINS A		A1	Gehalt an harten Mineralien (Ritzhärte H > 6)	%	unbedeutend < 5	klein 5-30	mittel 30-60	gross > 60
		A2	Gehalt an weichen Mineralien (Ritzhärte H < 3)	%	unbedeutend < 5	klein 5-30	mittel 30-60	gross > 60
		A3	Ungünstige Bestandteile	%	unbedeutend < 5	klein 5-30	mittel 30-60	gross > 60
		A4	Gehalt an quellfähigen Mineralien	%	unbedeutend < 3	klein 3-10	mittel 10-30	gross > 30
		A5	Quellpotenzial	N/mm² / %	nicht quellfähig	gering < 0.5 / < 3	mittel 0.5-3 / 3-15	hoch > 3 / > 15
		A6	Verhalten bei Wasserzutritt	-	unverändert (unempfindlich)	geringe / langsame Festigkeitsreduktion	grosse / rasche Festigkeitsreduktion	gänzlicher Festigkeitsverlust
		A7	Einaxiale Zylinderdruck-festigkeit *d*	N/mm²	sehr hoch > 200	mittel bis hoch 80-200	klein bis mittel 10-80	sehr klein < 10
		A8	Strukturanisotropie	-	massig (isotrop)	gering anisotrop	mittel anisotrop	stark anisotrop
		A9	Abrasivität	CAI / LCPC g/t	kaum abrasiv < 1 / < 300	abrasiv 1-2.5 / 300-800	sehr abrasiv 2.5-4 / 800-1300	extrem abrasiv > 4 / > 1300
EIGENSCHAFTEN DES GESTEINS B	SCHICHTUNG/ SCHIEFERUNG	B1	Abstand der effektiven Trennflächen	m	massig > 2	grob geschichtet 0.6-2	dünn geschichtet 0.06-0.6	feinschichtig bis blättrig < 0.06
		B2	Raumlage bezüglich Bauwerksachse	° (360)	sehr günstig > 60	günstig 30-60	ungünstig 15-30	sehr ungünstig < 15
		B3	Reibungswinkel in Schicht- bzw. Schieferungsfugen χπ	° (360)	gross > 40	mittel 30-40	klein 20-30	sehr klein < 20
		B4	Kohäsion in Schicht- bzw. Schieferungs-fugen c	N/mm²	gross > 2	mittel 0.2-2	klein 0.02-0.2	sehr klein < 0.02
	HAUPTKLÜFTUNG	B5	Abstand der effektiven Trennflächen	m	weitständig > 2	mittelständig 0.6-2	engständig 0.06-0.6	sehr engständig < 0.06
		B6	Raumlage bezüglich Bauwerksachse	° (360)	sehr günstig > 60	günstig 30-60	ungünstig 15-30	sehr ungünstig < 15
		B7	Lineare Erstreckung	m	gering < 1	mittel 1-3	gross 3-6	sehr gross > 6
		B8	Öffnungsweite und Füllung	mm	geschlossen < 0.5	wenig geöffnet (Füllmaterial mit Kohäsion) 0.5-5	wenig geöffnet (Füllmaterial ohne Kohäsion) 0.5-5	offen > 5
		B9	Reibungswinkel χπ	° (360)	gross > 40	mittel 30-40	klein 20-30	sehr klein < 20
		B10	Kohäsion c	N/mm²	gross > 2	mittel 0.2-2	klein 0.02-0.2	sehr klein < 0.02
TRENN-FLÄCHEN-KÖRPER C		C1	Grundform c/a	%	vorwiegend kubisch > 60	teilweise kubisch 40-60	teilweise plattig oder prismatisch 20-40	vorwiegend plattig oder prismatisch < 20
		C2	Maximale Abmessung (a-Wert)	m	gross > 2	mittel 0.6-2	klein 0.06-0.6	sehr klein < 0.06
HYDROGEOLOGIE D		D1	Art der Zirkulation	-	keine	Poren	Trennflächen	Karst
		D2	Druckhöhe (Höhe über Bauwerkssohle)	m	< 10	10-50	50-100	> 100
		D3	Transmissivität	m²/s	sehr klein (dicht) < $1x10^{-9}$	klein $1x10^{-9}$-$1x10^{-7}$	mittel $1x10^{-7}$-$1x10^{-5}$	gross > $1x10^{-5}$
		D4	Bergwasseranfall im Hohlraum	-	trocken	Tropfstellen, einzelne kleine Quellen	häufige kleine Quellen, vereinzelte grosse Quellen	häufige grosse Quellen, starker Wasseranfall
		D5	Wasserqualität	-	na: nicht aggressiv (<= Xa1) / a: aggressiv (Xa2 + Xa3)			
FEST-GESTEIN E		E1	E-Modul (geschätzt)	GPa				
		E2	Radioaktivität	cps µSv/h				
		E3	Gebirgstemperatur	°C				

Figure 28. SIA 199-compliant representation of a geological profile section. The figure includes tabular descriptions of the geological, hydrogeological and geotechnical rock properties.

6.1.1.3 Results

The orientation of the interfaces between the geological mapping units at the terrain surface could be derived as their occurrence at depth was also known (Figure 29A). This was achieved by taking into account the outcrop line of geological boundaries on the earth surface and by using reference points along the tunnel profiles from the detailed project.

For the second tube of the Gotthard road tunnel, the subsurface is comparatively well known, as experience has already been gained with the first tube (green in Figure 29B) and a safety tunnel. Starting from the safety tunnel, a large number of short exploratory boreholes were drilled in the direction of the second tube. However, the 3D model created from the retroperspective based on two tunnel profiles is anything but precise. The reason for this is the inaccuracy that arises when existing tunnel profiles are re-digitised and interpolated into 3D and further processed at a later point of time. The example therefore serves mainly to illustrate the idea and less as a basis for further planning.

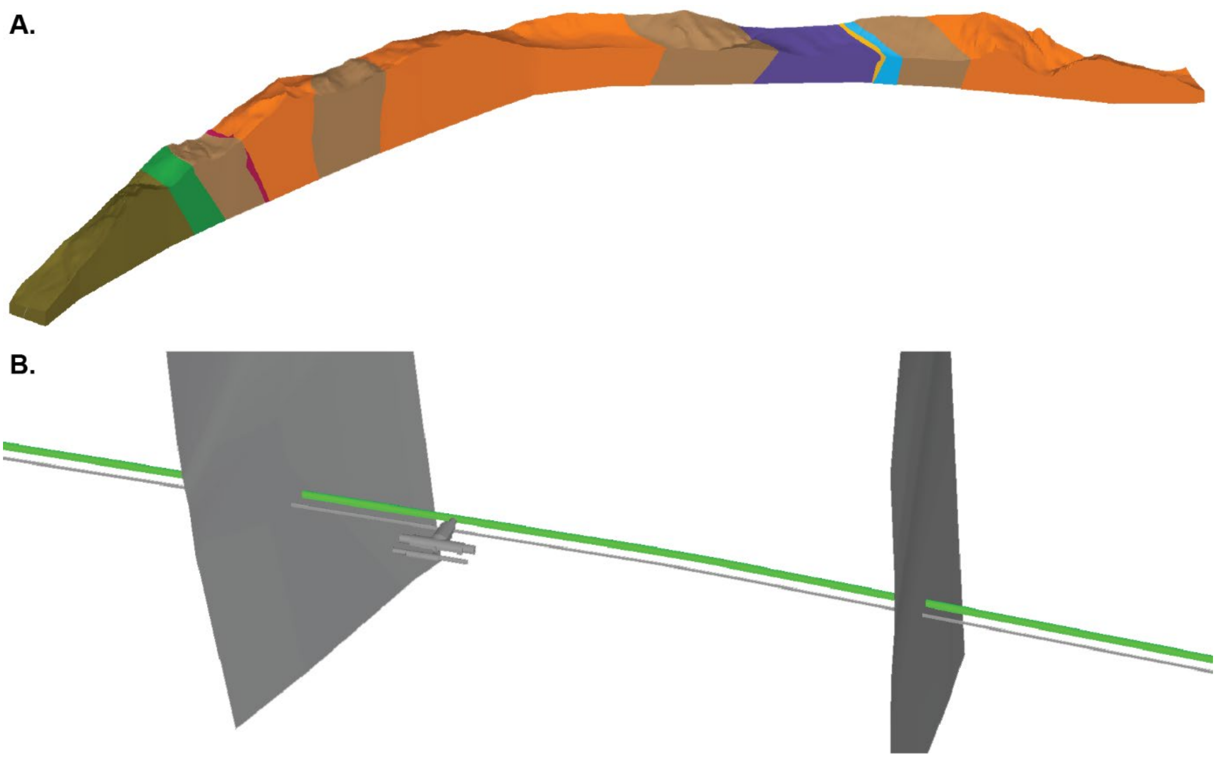
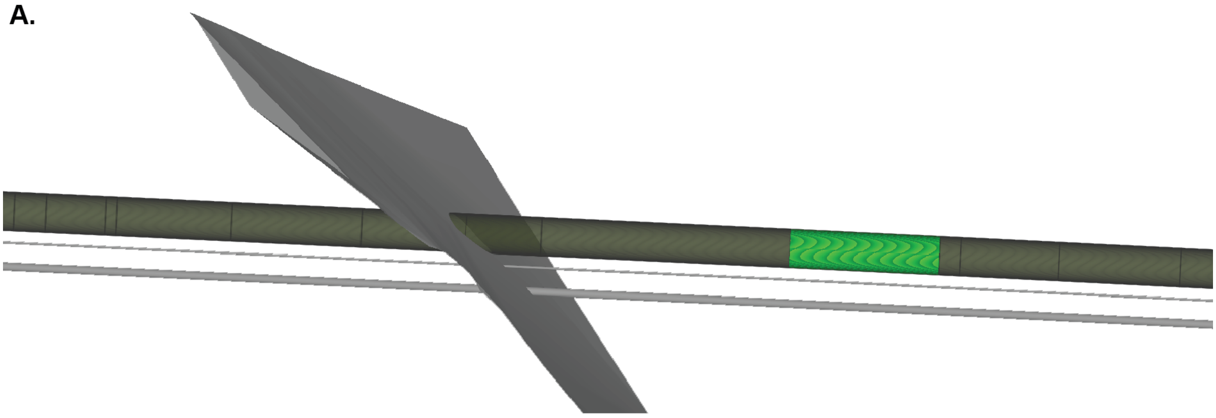


Figure 29. Retroperspective 3D modelling of the geology of the Gotthard road tunnel. The figure shows the geological mapping units (A) at the earth surface along the tunnel axis and the first tube of the Gotthard road tunnel (green in B) next to the safety tunnel and the ventilation centre (B). It also shows the modelled interfaces between the geological mapping units (grey areas in B).

In addition to the first tunnel tube and the safety tunnel shown in Figure 29B, it is possible to represent an SIA 199-compliant "tunnel tube" in the digital building model. To distinguish this more clearly from the structure of the first tube imported from CAD, the tunnel tube was given a thicker diameter (Figure 30A). This new object types are prediction intervals for the rock properties in the respective region. The clickable intervals in the three-dimensional space (green in Figure 30A) represent what is shown in tabular form under the geological profile according to the conventional method of working in accordance with the standard SIA 199 (Figure 28A) – the geological, hydrogeological and geotechnical descriptions of the rock properties. For communication via digital building models, only relevant properties of the marked prediction interval appear in the BIM viewer (Figure 30B).

A.



B.

A1 Gehalt an harten Mineralien (Ritzhaerte H > 6)	mittel (30-60%) - gross (> 60%)
A2 Gehalt an weichen Mineralien (Ritzhaerte H < 3)	klein (5-30%) - mittel (30-60%)
A3 Unguenstige Bestandteile	mittel (30-60%)
A4 Gehalt an quellfaehigen Mineralien	unbedeutend (< 3%)
A5 Quellpotential	nicht quellfähig
A6 Verhalten bei Wasserzutritt	unverändert (unempfindlich) - geringe / langsame Festigkeitsreduktion
A7 Einaxiale Zylinderdruckfestigkeit	mittel bis hoch (80-200 N/mm^2) - klein bis mittel (10-80 N/mm^2)
A8 Strukturanisotropie	mittel anisotrop
A9 Abravistitaet	sehr abrasiv (2.5-4 CAI/LCPC / 800-1300 g/t)
B1 Abstand der effektiven Trennflaechen	dünn geschichtet (0.06-0.6 m) - feinschichtig bis blättrig (< 0.06 m)
B10 Kohaesion in der Hauptklueftung (K1 + K2)	klein (0.02-0.2 N/mm^2) - sehr klein (< 0.02 N/mm^2)
B10s Kohäsion in Stoerzonen, Kakirit-, Lamprophyrscherzonen	klein (0.02-0.2 N/mm^2) - sehr klein (< 0.02 N/mm^2)
B2 Raumlage bezgl. Bauwerksachse	günstig (30-60°)
B3 Reibungswinkel in Schicht- bzw. Schieferungsfugen	klein (20-30°)
B4 Kohaesion in Schicht bzw. Schieferungsfugen	klein (0.02-0.2 N/mm^2) - sehr klein (< 0.02 N/mm^2)
B5 Abstand der effektiven Trennflaechen in der Hauptklueftung (K1 + K2)	mittelständig (0.6-2 m)
B5s Abstand der effektiven Trennflaechen in Stoerzonen, Kakirit-, Lamprophyrscherzonen	mittelständig (0.6-2 m)
B6 Raumlage bezgl. Bauwerksachse in der Hauptklueftung (K1 + K2)	günstig (30-60°)
B6s Raumlage bezüglich Bauwerksachse in Stoerzonen, Kakirit-, Lamprophyrscherzonen	ungünstig (15-30°)
B7 Lineare Erstreckung in der Hauptklueftung (K1 + K2)	gering (< 1 m)
B7s Lineare Erstreckung in Stoerzonen, Kakirit-, Lamprophyrscherzonen	gross (3-6 m)
B8 Öffnungsweite und Fuellung in der Hauptklueftung (K1 + K2)	geschlossen (< 0.5 mm)
B8s Öffnungsweite und Fuellung in Stoerzonen, Kakirit-, Lamprophyrscherzonen	wenig geöffnet, Füllmaterial ohne Kohäsion (0.5-5 mm) - offen (> 5 mm)
B9 Reibungswinkel in der Hauptklueftung (K1 + K2)	klein (20-30°) - sehr klein (< 20°)
B9s Reibungswinkel in Stoerzonen, Kakirit-, Lamprophyrscherzonen	klein (20-30°)
C1 Grundform c/a	teilweise plattig oder prismatisch (20-40%) - vorwiegend plattig oder prismatisch (< 20%)
C2 Maximale Abmessung (a-Wert)	mittel (0.6-2 m) - klein (0.06-0.6 m)
D1 Art der Zirkulation	Trennflächen
D2 Druckhoehe (Hoehe über Bauerkssohle)	> 100 m
D3 Transmissivitaet	klein (1x10-9 - 1x10-7 m^2/s)
D4 Bergwasseranfall im Hohlraum	trocken
D5 Wasserqualitaet	aggressiv (Xa2 + Xa3)

Figure 30. SIA 199-compliant mapping of rock properties in a BIM viewer. The figure shows the prediction intervals of the rock properties (thick tube in A). For the selected interval (green in A), only the relevant geological, hydrogeological and geotechnical properties for the respective section are shown (B).

6.1.1.4 Findings

A SIA 199-compliant transfer of geological, hydrogeological and geotechnical investigation results to digital construction models offers several advantages:

- The geological, hydrogeological and geotechnical expertise can be incorporated into the cooperation via a joint coordination model using the BIM method. This means that the spatially located results can be presented and discussed directly alongside those of other domain experts.
- The three-dimensional representation improves the understanding of the geometries, whose sometimes complex structures can only be inadequately captured in cross sections.
- Should it become possible in future to define a workflow that automatically combines all geological, hydrogeological and geotechnical descriptions of the rock mass properties with the geometries from the 3D modelling, the SIA 199-compliant deliverables can be generated with less effort

in the communication from geologists to engineers. This is particularly relevant when frequent revisions are required in an iterative process of collaboration between geologist and engineer.

The following aspects prove to be problematic.

- The IFC standard is in continuous development (version 4.x) and is currently mostly used in the BIM-specific environment with manufacturer-specific adaptations. Often old versions (e.g. version 2.3) are still in use. This frequently results in compatibility problems when importing and exporting IFC files with other programs that are necessary for processing.

- In the present interdisciplinary field of geology and engineering, there is hardly any software available with which input data and end products can be displayed together. Different software packages often have to be used at considerable cost. However, the generation in a single software package or at least the joint presentation of basics and implementation would be necessary to check the validity of the entire workflow.

- The local inaccuracy of data, mostly the location of layer boundaries or the occurrence of fractures, fault zones or the groundwater level is currently often difficult to represent. In most cases, the most probable position or a possible spatial range of fluctuation (especially in the case of groundwater levels) is shown graphically, e.g. in a profile. This is relatively easy to show in a drawn 2D profile, e.g. by means of dashed lines. However, these only have a decorative or explanatory character. Fixed limits for the spatial validity of the parameters must be specified for the geological model. This is why in the geological model only the most probable location is usually given and its validity is discussed in the text or dealt with via variants. In future, geostatistical analysis methods would have to be incorporated into the process right from the start and their results would have to be transferable to the digital building model.

6.1.2 **Insertion of a passenger subway at Basel Muttenz station**

6.1.2.1 Initial situation

During a weekend closure on 11 and 12 December 2021, a prefabricated passenger subway was inserted under the track at Basel Muttenz station. In a temporary excavation pit dug for this purpose, the component was first prepared next to the track (Figure 31A) and then slid in during the track closure (Figure 31B). The geological subsoil also played a role in the dimensioning of all construction elements for securing the excavation pit. In the BIM@SBB pilot project "Digitale Baustelle" (Digital Construction Site), the implementation phase of the insertion was closely accompanied by the Swiss Federal Railways SBB and in-Terra GmbH. The pilot study asks fundamental questions about the handling of geological and geotechnical information of the subsoil and the staging of excavation phases during the realisation phase of civil engineering projects.

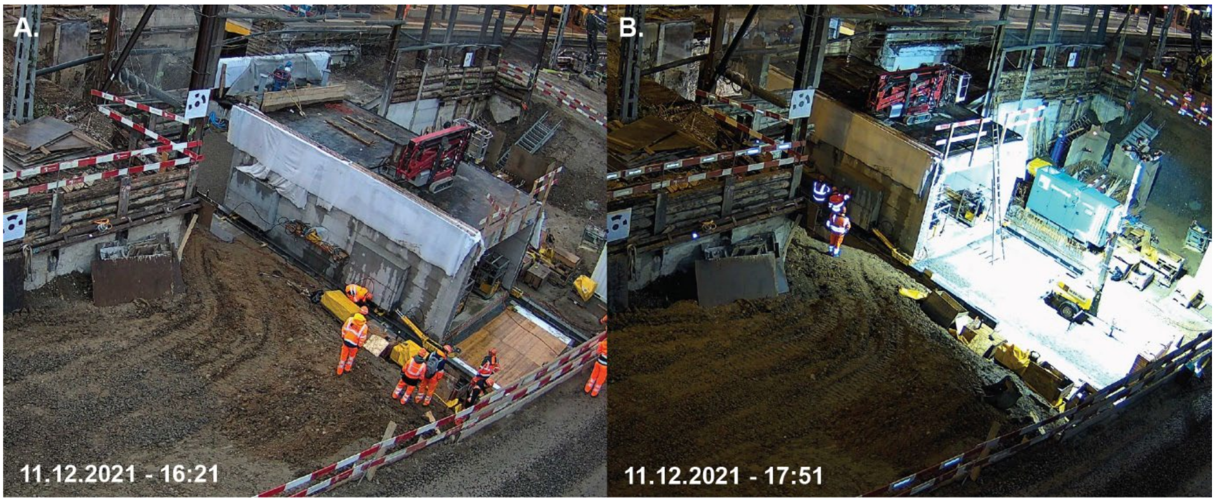


Figure 31. Two photos of the realisation phase of the project show how a passenger subway is slid under the track of the Swiss Federal Railways SBB at Basel Muttenz station during a weekend closure in December 2021.

6.1.2.2 Procedure

Before the first construction work was carried out, the zero state of the terrain surface was surveyed with the help of drone images (beige in Figure 32A). There was too little structured information about the nature of the geological subsoil for a data-based three-dimensional subsoil model. In order to be able to evaluate the possibilities in the future use of the subsoil, two fictitious interfaces were added to the digital building model. On the one hand, a geological formation boundary in the unconsolidated rock separates a fine-grained cover layer from an underlying layer of gravel (red in Figure 32A). On the other hand, the hydrogeological interface of a groundwater table separates water-saturated areas at depth from unsaturated areas near the earth's surface (blue in Figure 32A).

Below the ground surface determined through drone images, the geological subsoil (half-space below the terrain surface) was decomposed into units of homogeneous geotechnical properties using the interfaces and Boolean operators (Figure 32B and Figure 32C). In addition, the excavation depths known from planning were taken into account to quantify the volumetric quantities of excavated material per geological unit (Figure 32B).

A.

B.

C.

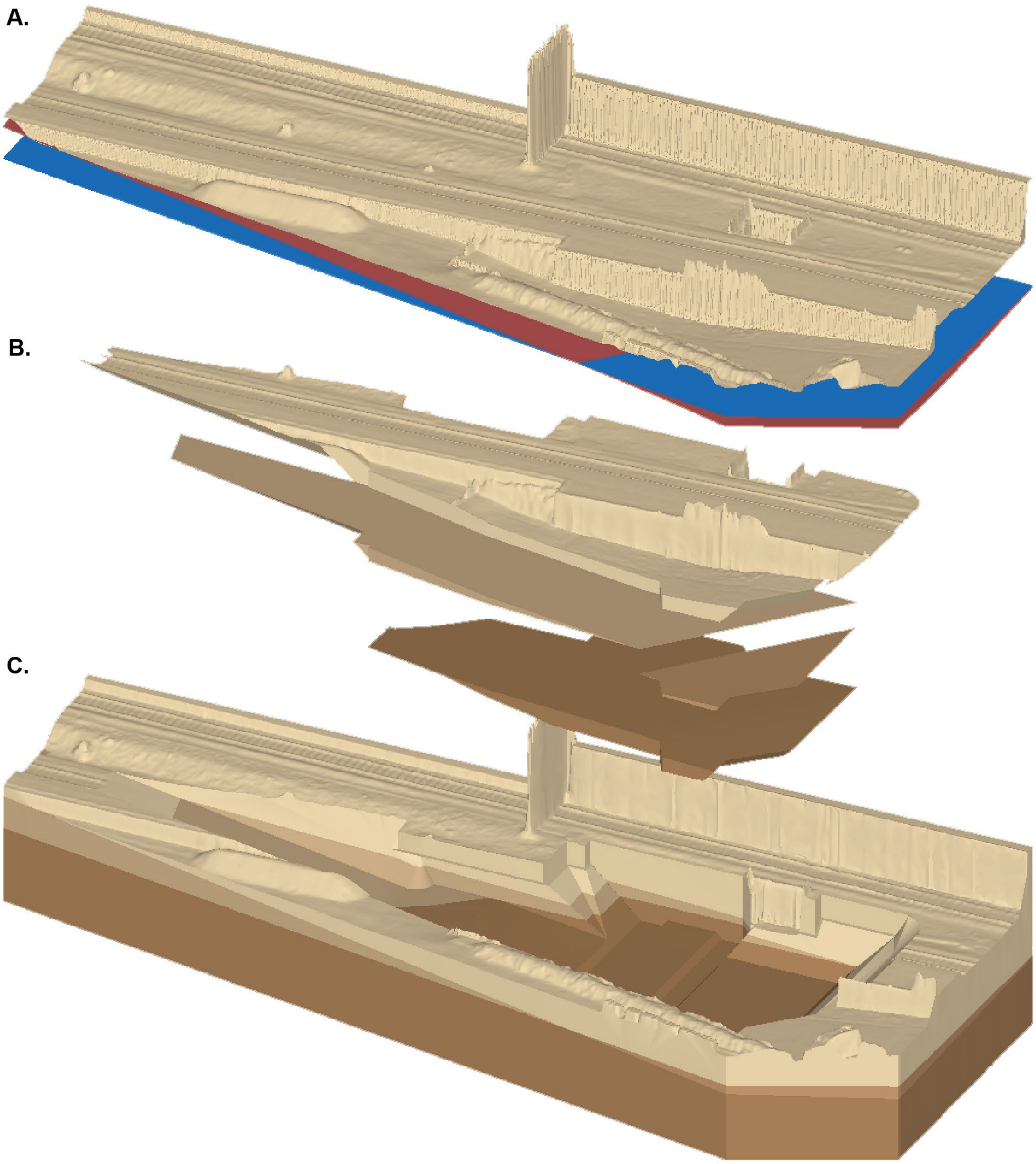


Figure 32. Terrain surface and geological structures and units in Basel Muttenz. Ground surface (beige in A), geological formation boundary (red in A), groundwater level (blue in A), as well as four subsoil areas (beige/brown tones) inside (B) and outside (C) of the excavation pit in the digital construction model, which differ in terms of their geological and geotechnical properties.

6.1.2.3 Results

Taking into account the geological formation boundary and the groundwater level (Figure 32A), four units each can be distinguished inside and outside the excavation pit. 1. Gravel below the water table, 2. Gravel above the water table, 3. The top layer below the water table 4. The top layer above the water table (Figure 32B and Figure 32C). Since "watertight" interfaces (in a geometric not hydrologic sense) have been generated using Boolean operators (Figure 32B), many modern BIM viewers automatically calculate the volumetric quantities of excavated material in m^3 per geological unit.

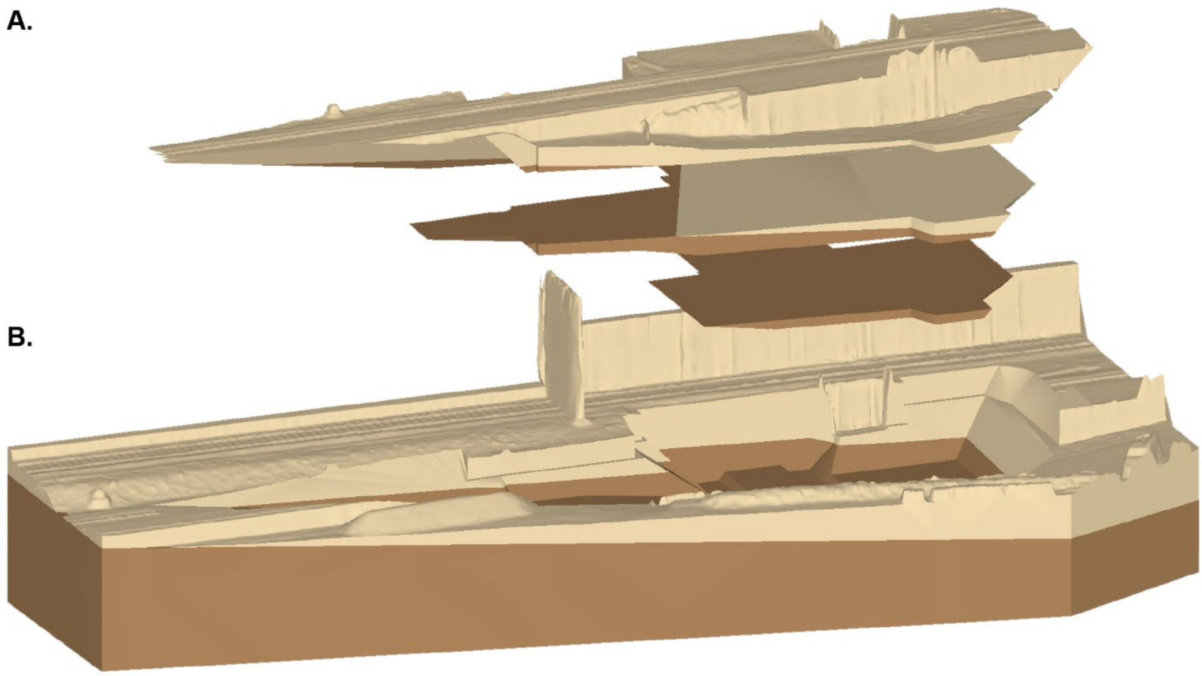


Figure 33. Illustration of the excavation phases using the example of the geology in Basel Muttenz. Staging of the excavation in three phases (A) above the geological model of the surroundings outside the excavation pit (B). A distinction is made between a fine-grained surface layer (beige) and underlying gravel (brown).

The excavation of an excavation pit can also be viewed from the perspective of the individual staging phases. Figure 33A illustrates the planning of the excavation of the excavation pit in three phases. In each of the phases, excavation is carried out to a defined depth – parallel to the ground surface.
The volumetric material quantities per stage can be read out if the corresponding areas are enveloped again by “watertight” interfaces. Such questions are always of particular relevance when it has to be decided whether the removed material can be reused or even has to be disposed of separately.

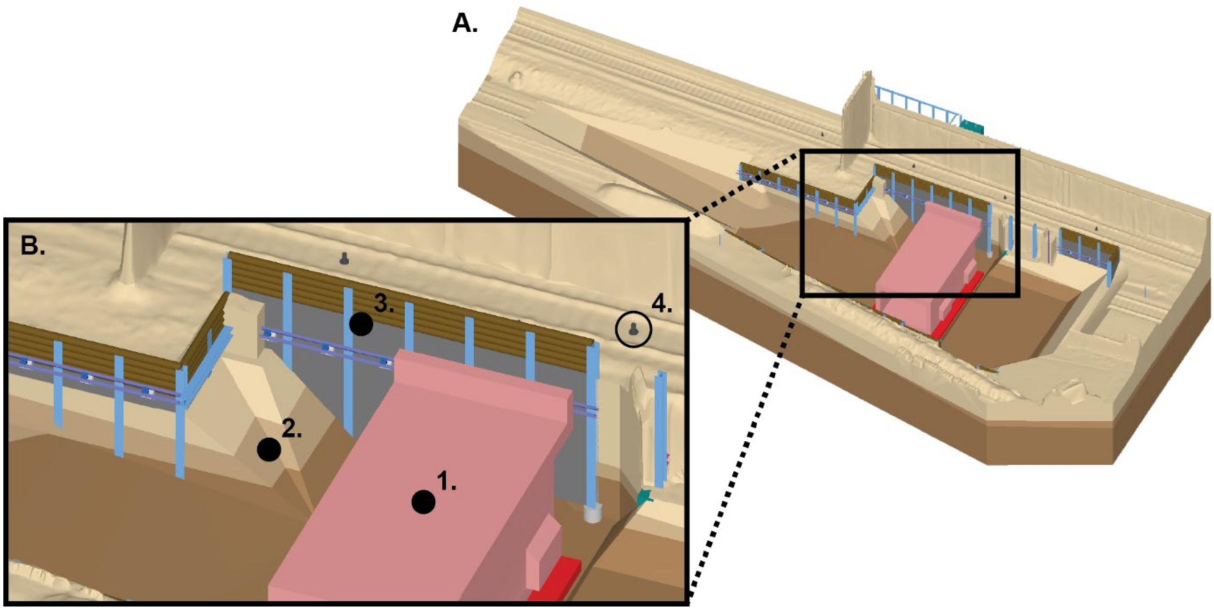


Figure 34. Combined representation of the geological model with the construction elements in Basel Muttenz. Digital construction model of all geotechnical construction elements for temporary excavation support (A). The enlarged section (B) shows the prefabricated pedestrian subway before insertion (1), the geological formations on the excavation pit wall (2), the soldier pile walls and the tensioned anchorages (3) and the measuring points of the plate bearing tests (4).

The exchange of information is crucial for cooperation in the construction project, when using the BIM method or in digital building models (Figure 34A and Figure 34B). Ideally, the information to be exchanged is reduced to what is absolutely necessary. The present pilot study is limited to the description of the properties of geological units (Figure 34B-2) and recommends the twelve geotechnical properties of geological formations in the subsoil summarised in Table 6.

Table 1. Geotechnical properties of geological formations in the subsoil.

No.	Property	Abbreviation	Unit
1.	Effective angle of internal friction	ϕ'	° (360°)
2.	Moisture-proof weight	γ	$kN \cdot m^{-3}$
3.	Effective cohesion	c'	kPa
4.	Compression modulus, initial load	M_{E1}	MPa
5.	Compression modulus, reloading	M_{E2}	MPa
6.	Hydraulic permeability	k	m/s
7.	Water content	w	%
8.	Uniaxial compressive strength	q_u	kPa
9.	Undrained shear strength	c_u	kPa
10.	Specific volume weight	γ_s	$kN \cdot m^{-3}$
11.	Porosity	n	%
12.	Bedding modulus	k_s	$kN \cdot m^{-3}$

For communication during cooperation in the construction project, the interfaces surrounding the geological units were chosen to represent the geology in the digital construction model (Figure 34A and Figure 34B). This has the advantage that sections through the building model allow a view into the interior of the formation. In this way, the geotechnical construction elements located inside to stabilise the excavation pit can be easily seen through the entire formation (Figure 35). This approach is aimed at a recipient of the information for whom the construction elements for securing the excavation pit have priority. This methodology is not suitable for the automatic generation of classical geological profile sections.

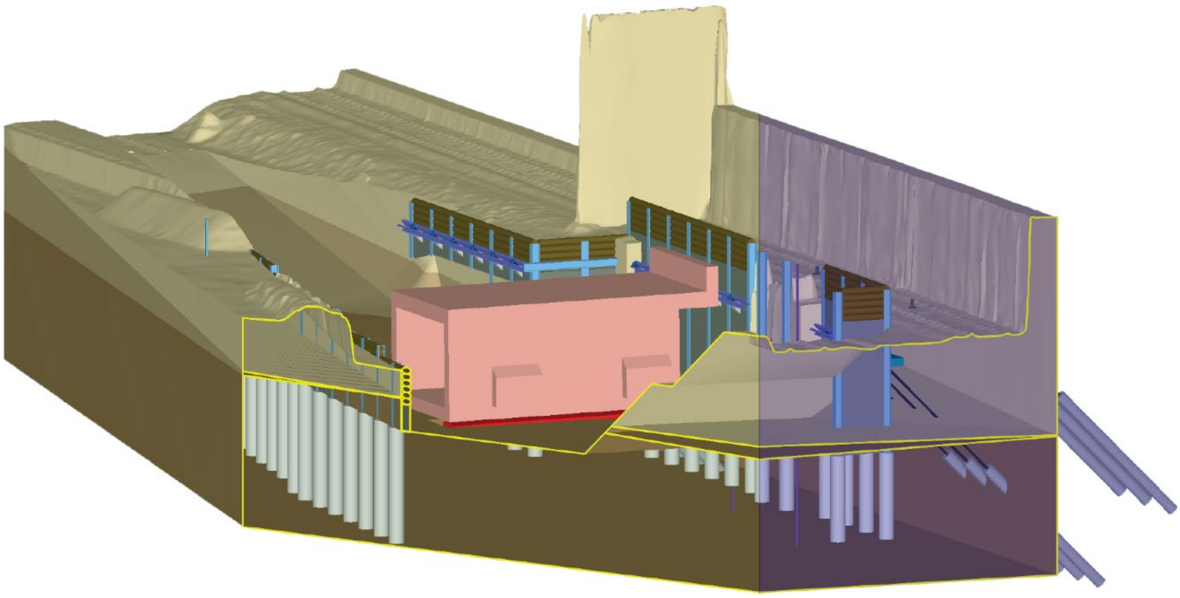


Figure 35. Sections through the geology of the building ground model in Basel Muttenz. Folded profile section through the digital construction model of the excavation pit for the insertion of the passenger subway at Basel Muttenz station.

6.1.2.4 Findings

Combining information on the geological subsoil with drone surveys of the ground surface and the construction elements for securing the excavation pit brings several advantages.

- Through the equivalent visualisation of the geological subsoil in the context of all construction elements in 3D, the geology is perceived as relevant to the structure.
- Sections through the subsoil allow the load-bearing geological unit of an anchor or a structural element to be identified at a glance.
- The locations where samples are taken or tests are carried out can be represented directly as objects in the digital building model. The test results of the individual measurement or metadata such as the company carrying out the measurement or the person responsible can be attributed directly to the object.
- The attribution of geological units with geotechnical property values makes it possible, for example, to attach the resulting values of all the individual measurements taken into account and the uncertainties of a series of tests to a clickable object. This makes it possible for the cooperation to specifically provide the results of statistically evaluated test series or recommendations for interpreted values.
- Using the features for analysing model elements, the volume of a geological unit in m^3 can be quantitatively calculated in the BIM viewer.
- In addition to the representation of geological units, the staging phases can also be planned quantitatively. In combination with the geological units, it is even possible to quantify how much of which geological unit is produced in which excavation phase.
- Recurring drone surveys of the ground surface at regular intervals make it possible to record the excavation progress and the removal of soil material on the construction site as a temporally resolved process. This enables an automated target-actual comparison between planning and execution.

However, the new possibilities in handling geological information in digital building models also come with some previously unsolved challenges.

- Subsoil models should also be continued during construction. However, the findings from the realisation phase should be added. Often geologists are no longer on site during construction and are only called in for specific questions, usually when problems arise. Crucial processes and roles for tracking geological information during construction are therefore not yet defined.
- Open geological interfaces can already be routinely created and edited with many software products. “Watertight” interfaces around geological units are much harder to create and there is a lack of automated tools to process them.
- For the efficient and effective handling of self-contained ("watertight") interfaces around geological units, there is also a lack of tools for the subtraction or addition of two units (Boolean operators) that are consistently integrated into the existing workflows.
- BIM viewers are often not yet capable of displaying the interfaces surrounding a unit in a way that is not merely hollow. For the visualisation of classical geological cross sections it should be possible to switch between polygons filled along the section surface and the hollow display mode.

6.1.3 **Geological models in civil engineering and underground mining**

6.1.3.1 Initial situation

The case study lies in the Upper Freshwater Molasse (Oberen Süsswassermolasse, OSM) area of the uplifted Midland Molasse (mittelländische Molasse) with a relatively low cover of unconsolidated rocks (moraine, artificial fills). The project is an underground construction geologically supervised by CSD Ingenieure AG, most of which is in rock. With regard to the project planning and construction of the project, the rock mass had to be assessed geologically, geotechnically and hydrogeologically in accordance with the national standard SN 531199:2015 (SN531199:2015; SIA 199, 2015). As a basis for the dimensioning of the project and securing of the excavation pit, geotechnical parameters (primarily rock mechanical parameters) were to be assigned in particular to the units in the rock.

The OSM consists largely of detrital sedimentary rocks deposited in a large river system in which different facies or "geological architectural elements" occur (Keller, 1992) (Figure 36). Depending on the situation, the facies or architectural elements allow a large-scale correlation and can thus be represented accordingly in a 3D model. In the present case study, these units were therefore chosen for the subdivision of the rock mass (homogeneous areas in first approximation) and for the 3D modelling.

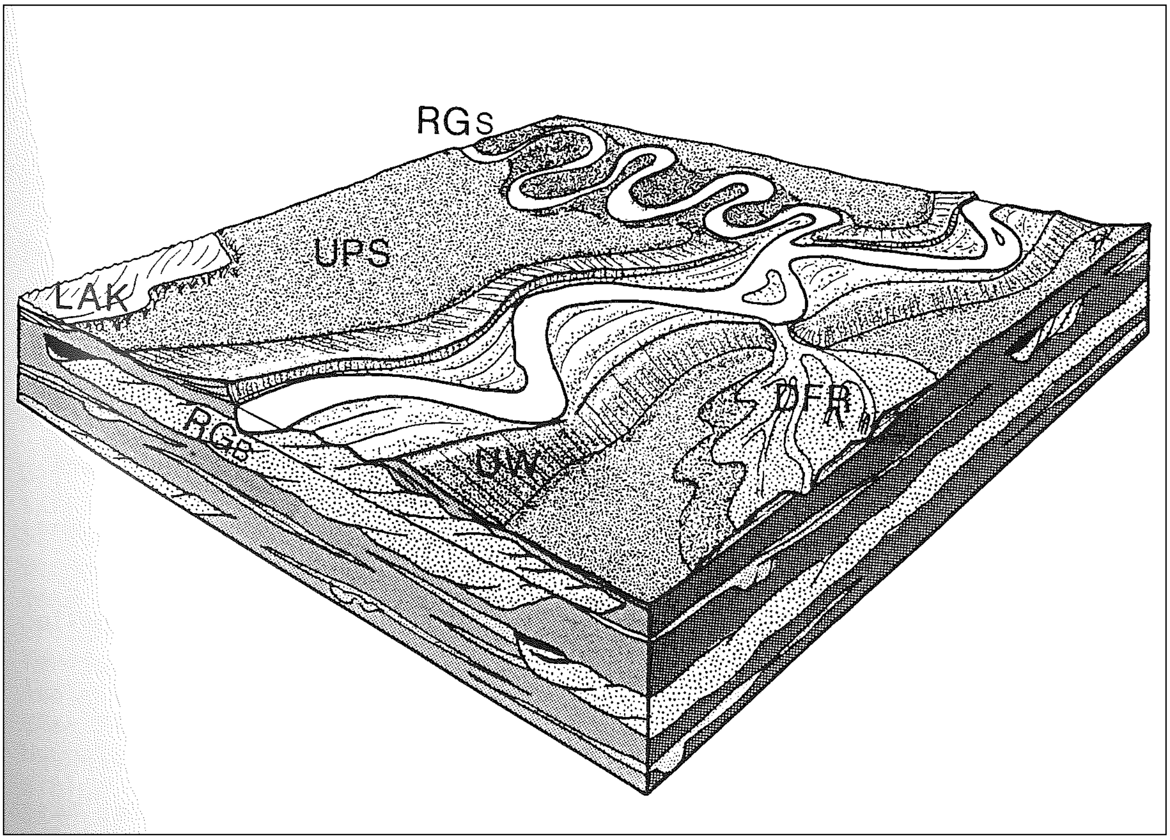


Figure 36. Architectural elements of the Upper Freshwater Molasse (Oberen Süsswassermolasse – OSM). Schematic block diagram of the depositional area at the time of the OSM with the architectural elements RGS, RGB, DFR, UW, UPS and LAK (Ammann et al., 1993).

6.1.3.2 Procedure

Core drillings were carried out to clarify the geotechnical issues. To investigate the anisotropy, these core drillings were partly carried out perpendicular to the stratification in order to be able to take and analyse appropriately oriented core samples. During the geological recording of the drill cores, the individual layers were each assigned to one of seven lithotypes. The differentiation of the lithotypes is based on the lithological properties of the individual layers, mainly grain size and degree of cementation, but also other properties such as petrographic composition or the content of organic (carbonaceous) material.

Numerous samples were also taken from the cores for various rock mechanics laboratory tests (uniaxial compression tests, triaxial tests, point load tests, swelling tests, etc.). The samples were chosen in such a way that—seen over the entire exploratory campaign—all lithotypes could be characterised with sufficient samples or laboratory tests.

The laboratory values were statistically evaluated separately for each lithotype (minimum, maximum, arithmetic means, 5% quantiles, etc.). Taking into account older investigations in the area, the borehole tests carried out (hydraulic packer tests, dilatometer tests, etc.), characteristic values were derived for each lithotype.

The subdivision into lithotypes represents a first generalisation of the detailed drill core survey. Although it provides very good resolution, it is hardly possible to correlate over larger distances. For the further generalisation step to the facies model, the soundings with their lithotypes (colour code) were loaded into the 3D modelling software Move™. In several processing cycles in 3D space and on 2D sections, the respective facies were delineated with the help of the lithotype sequence in the soundings, the general layer orientation (according to bibliographical data and information from borehole scans), the architectural elements (geometries) and other geological information (e.g. feature profiles of existing tunnels etc.). The delimitation was carried out in each case as a lower limit by means of an interpolated area. Individual horizons can be correlated well, e.g. thicker sandstone beds from the RG facies or large coal layers from the UPS facies. Others are more diffusely distributed and less clearly delineated. A facies consists of different lithotypes ("parageneses") and each lithotype can occur in different facies. The facies model therefore requires in-depth geological knowledge of the sedimentary deposition processes and the resulting geometries.

In order to be able to assign the geotechnical parameters determined on the lithotypes to the separated facies, the boreholes were again used: The "distances" of the lithotypes in the boreholes per facies layer were statistically evaluated and thus the proportions of the lithotypes contained therein were assigned to each facies layer. In a next step, this distribution can be used to transfer the geotechnical parameters of the individual lithotypes into a facies layer. A similar approach was taken for other properties, such as the bed-like jointing capacity.

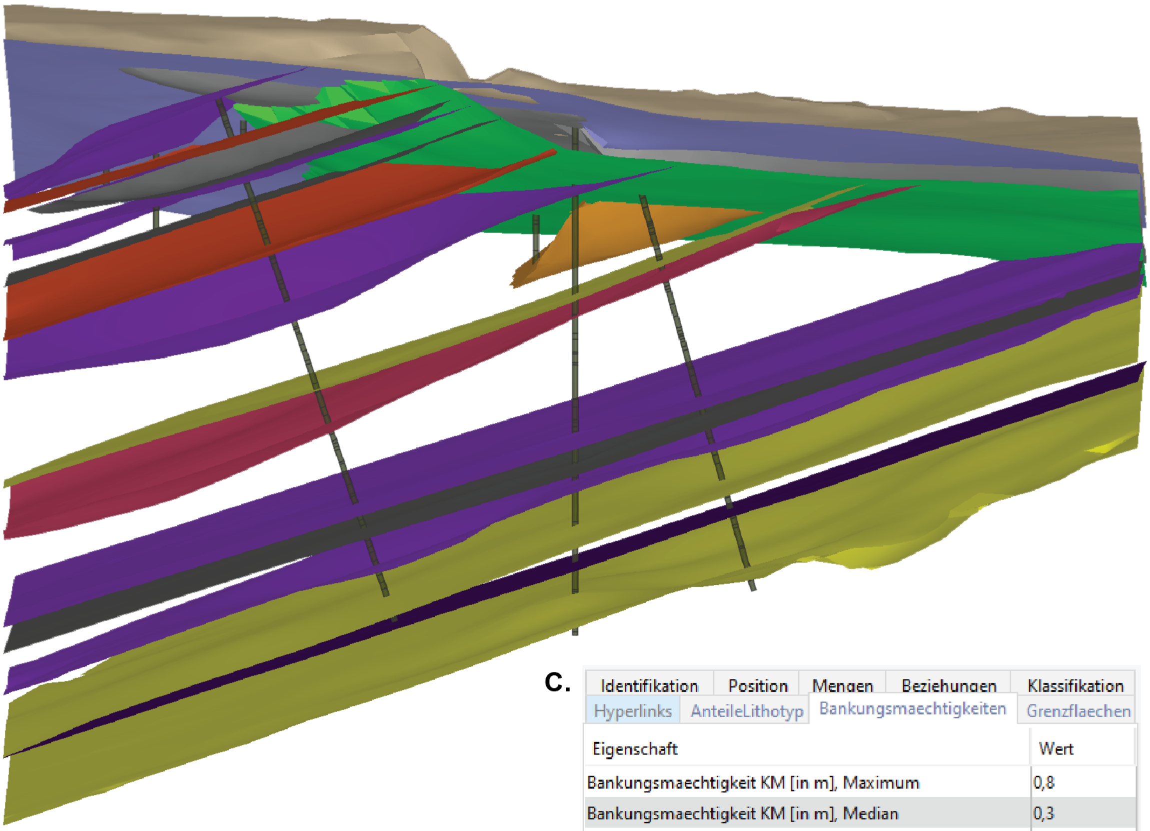
For the application of the BIM method to communicate the results via digital building models, the results of the geological 3D modelling were exported into the data exchange format DXF, which was developed by Autodesk but is openly documented. With the help of the transformers developed in the GEOL_BIM Innovation Project, the geometries exported to DXF were converted into the open IFC data exchange format developed by BuildingSMART and standardised internationally in accordance with SN EN ISO 16739:2016 (SN EN ISO 16739, 2016). The converted geometries were attributed with the alpha-numerical results of all geotechnical investigations and drilling campaigns, which were mainly available in Microsoft Excel.

6.1.3.3 Results

In the digital subsoil model, parameters such as the proportions of the lithotypes (Figure 37B), the bedding thickness (Figure 37C) and the uncertainties of these parameters (Figure 37B and Figure 37C) can now be retrieved for each facies layer (Figure 37A). The geotechnical parameters available for each individual lithotype can be transferred to the facies layer via the proportions of the lithotypes. On the one hand, the bedding thickness provides qualitative information about how heterogeneous a facies layer is (smaller beds = more change of lithologies), on the other hand it is an important parameter for certain geotechnical calculations, e.g. the swelling capacity of clayey layers. The uncertainties are also indicated by always taking the maxima and minima from the statistical evaluations. Thus, even after processing and simplification, it is still possible to see how large the scatter of the lithological distribution is and, to a certain extent, it is also possible to assess the reliability of the geotechnical parameters assigned to a facies.

Different statistical values (minima, maxima, 5% quantiles, arithmetic means, median, etc.) are given for the characteristic values of the lithotypes, since a different input parameter makes sense depending on the technical problem. Note: In this specific case, all these values are based on laboratory data determined on borehole information.

A.



B.

Identifikation | Position | Mengen | Beziehungen | Klassifikation
Hyperlinks | AnteileLithotyp | Bankungsmaechtigkeiten | Grenzflaechen

Eigenschaft	Wert
Anteil Lithotyp KM [in Prozent], arithmetischer Mittelwert	20
Anteil Lithotyp KM [in Prozent], gewichteter Mittelwert	20
Anteil Lithotyp M [in Prozent], arithmetischer Mittelwert	49
Anteil Lithotyp M [in Prozent], gewichteter Mittelwert	52
Anteil Lithotyp MSST [in Prozent], arithmetischer Mittelwert	12
Anteil Lithotyp MSST [in Prozent], gewichteter Mittelwert	10
Anteil Lithotyp SIST [in Prozent], arithmetischer Mittelwert	5
Anteil Lithotyp SIST [in Prozent], gewichteter Mittelwert	4
Anteil Lithotyp SM [in Prozent], arithmetischer Mittelwert	11
Anteil Lithotyp SM [in Prozent], gewichteter Mittelwert	11
Anteil Lithotyp SST [in Prozent], arithmetischer Mittelwert	3
Anteil Lithotyp SST [in Prozent], gewichteter Mittelwert	4
Standardabweichung des Untersuchungsbereichs [in m]	2,16
Untersuchungsbereich entlang Bohrung [in m]	11,02

C.

Identifikation | Position | Mengen | Beziehungen | Klassifikation
Hyperlinks | AnteileLithotyp | Bankungsmaechtigkeiten | Grenzflaechen

Eigenschaft	Wert
Bankungsmaechtigkeit KM [in m], Maximum	0,8
Bankungsmaechtigkeit KM [in m], Median	0,3
Bankungsmaechtigkeit KM [in m], Minimum	0,2
Bankungsmaechtigkeit KM [in m], Mittelwert	0,3
Bankungsmaechtigkeit KM [in m], Standardabweichung	0,16
Bankungsmaechtigkeit KM, Anzahl Werte	18
Bankungsmaechtigkeit M [in m], Maximum	1,8
Bankungsmaechtigkeit M [in m], Median	0,7
Bankungsmaechtigkeit M [in m], Minimum	0,1
Bankungsmaechtigkeit M [in m], Mittelwert	0,8
Bankungsmaechtigkeit M [in m], Standardabweichung	0,47
Bankungsmaechtigkeit M, Anzahl Werte	21
Bankungsmaechtigkeit MSST [in m], Maximum	0,8
Bankungsmaechtigkeit MSST [in m], Median	0,4
Bankungsmaechtigkeit MSST [in m], Minimum	0,2
Bankungsmaechtigkeit MSST [in m], Mittelwert	0,5
Bankungsmaechtigkeit MSST [in m], Standardabweichung	0,22
Bankungsmaechtigkeit MSST, Anzahl Werte	7
Bankungsmaechtigkeit SIST [in m], Maximum	0,9
Bankungsmaechtigkeit SIST [in m], Median	0,6
Bankungsmaechtigkeit SIST [in m], Minimum	0,2
Bankungsmaechtigkeit SIST [in m], Mittelwert	0,6
Bankungsmaechtigkeit SIST [in m], Standardabweichung	0,49
Bankungsmaechtigkeit SIST, Anzahl Werte	2

Figure 37. Geological model transferred to a BIM viewer for collaboration. 3D facies model in the Molasse in a digital subsoil model (A), with the proportions of lithotypes (B) and the bedding thickness (C) for an exemplary selected facies. In addition to vertically drilled boreholes, boreholes were also drilled perpendicular to the stratification to investigate the anisotropy, so that appropriately oriented core samples could be taken and analysed.

6.1.3.4 Findings

There are several advantages to be gained from 3D geological modelling and the use of the BIM method to communicate the geological-geotechnical results.

- Better understanding of geometries of geological units (homogeneous areas, interfaces) through direct observation in 3D instead of only in sections.

- More realistic (truer) representation in sections if these are only created after the interpolation of the layer boundaries has taken place directly in 3D space (between findings correctly placed in space such as boreholes and exposures). This results in fewer "projection-related" effects/errors (auxiliary sections during the iterative modelling process are allowed).

- If the engineer needs to make a lot of sections, 3D modelling can significantly reduce the effort.

There are also hitherto unresolved challenges, which also offer numerous opportunities for further development in the future.

- Good basic data are required, e.g. several probings with detailed layer recording in the vicinity, sufficient drill cores and laboratory data for the evaluation of the characteristic values (increased requirements for drilling methods, sampling, sample preparation). This requires not only structured data storage, but also the possibility to process it easily and efficient workflows.

- The modelling of interlocks that frequently occur in detrital sediments is difficult and often not very useful. Strategies for simplification are needed here.

- The focus in this example was on the lithological distribution and the bedding thickness. The fracturing, faults and geotechnical parameters determined for lithotypes and facies were not considered or transferred to IFC. In the future, strategies and workflows would be needed to deal with such different perspectives.

- Exported geometries in DXF format vary depending on the way they have been modelled in the 3D geological software. The GEOL_BIM interface can currently only read a few of the DXF files exported from Move™, which can lead to errors when processing arbitrary geometries.

6.1.4 Results from finite element models in IFC

6.1.4.1 Initial situation

Different approaches to transfer the results from finite element methods (FE method or FEM) into the international standardised data exchange format IFC according to SN EN ISO 16739:2016 (SN EN ISO 16739, 2016) were investigated. Two objectives were pursued:

- Presentation of FE results such as settlements as a support in the communication between several parties involved in a construction project, and
- provision of an exchange format for communication between different calculation tools. As an example, the interaction between a geotechnical software and a structural modelling software is considered. The geotechnical software provides bedding stiffnesses that are applied as elastic springs to the structure foundation in order to take the interaction with the soil into account in the structure software.

6.1.4.2 Procedure

Ideally, IFC adopts the data structure of the FE model, i.e. the geometries of the elements are mapped and the attributes are adopted without further approximation. Unfortunately, there is currently no IFC structure for unstructured volume elements that allows this.

In collaboration with geoMod ingénieurs conseils SA and De Cérenville géotechnique SA, two approaches were therefore investigated as an approximation for presenting the results:

- Voxel models: Voxel models divide space into a regular mesh of rectangular hexahedra (cf. Fundamental Report Geology, in German). The storage of voxel geometries is very efficient because, starting from an origin point, only the cell size and number in each spatial axis need to be defined. The location of a voxel is then clearly given due to its consecutive numbering. Any number of attributes can be defined as vectors and assigned to the voxels via their indices.
- Isovolume: The space is divided into an arbitrary number of volume bodies, for each of which an attribute lies in a certain value range. The individual isovolumes are defined as closed surfaces constructed from polyhedra or triangles.

FE methods produce 2 types of results, node-based and element-based:

- In geotechnical engineering, node-based results are usually displacements and pore water stresses. Over the entire model domain, these results can be retrieved by continuous interpolation or approach functions at any point.
- Element-based results are typically strains, stresses and flows. Since they are derived from the derivatives of the interpolation functions, they are usually discontinuous from one element to the neighbouring one.

While for node-based results a continuous interpolation over the entire model domain is available via the trial functions, post-processing (keywords "smoothing" or "superconvergent patch recovery") is necessary for element-based results.

6.1.4.3 Results

The example of a new school building project in Renens illustrates the possibilities for the presentation and further use of FE results (Catsaros, 2017).

6.1.4.3.1 Case study: subgrade reaction moduli

The traditional division of labour between structural and geotechnical engineers has led to a specialisation of the fields of work, which is reflected in the structuring of study programmes and planning offices, the tendering of public contracts and the development of the corresponding software tools. For foundations of larger buildings, the division leads to the fact that soil-structure interaction is often not or only insufficiently considered due to missing interfaces. Here IFC, as a widely used exchange format, can make a contribution to simplifying the exchange of data between simulation tools.

The workflow can be described as follows:

- Modelling of the structure under quasi-permanent loads, assumption of a subgrade reaction modulus distribution under the foundation slab.
- Calculating interaction forces at foundation slab level.
- Creating a geotechnical model taking into account the geology, hydrology and construction process.
- Inserting the interaction forces (=structural loads) into the geotechnical model. The use of the IFC format could also provide valuable services in this step.
- Calculating the bedding stiffnesses based on the consolidation settlements and the invert pressures under the foundation slab.
- Inserting the bedding stiffnesses in the structural model (using the IFC file) and calculating an updated distribution of the structural loads.
- Repeating the process until compatibility of the consolidation settlements between the two submodels is given.

Since a continuous transition from stiffer to softer areas is desired in the workflow described and the area to be represented by the IFC model is limited to one element layer under the foundation slab, a voxel model is suitable for this application.

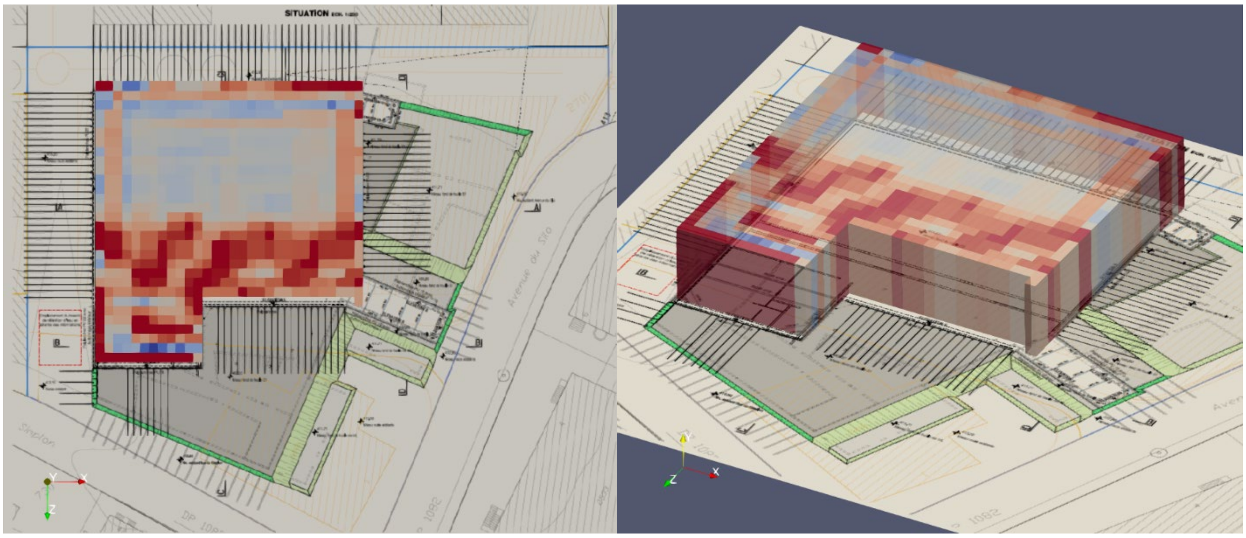


Figure 38. Bedding stiffnesses shown as a voxel model. Exemplary distribution of bedding stiffnesses from high (blue) to low values (red) over a partial area of the school facility in the map view (left) and in the perspective view (right).

6.1.4.3.2 Case study shifts

An export of consolidation settlements into a common exchange format provides the basis for comparing and discussing results, e.g. from a variant study, in the context of a meeting with several project participants. Different layers such as 3D building models, plant management and infrastructures, GIS data, etc. can be displayed in a BIM viewer together with the expected consolidation settlements.

For a quick and clear comparison of variants, representations with the help of isovolumes are suitable. For consolidation settlements or horizontal displacements, there are often limit values that must be observed in the area of certain objects. Their spatial limitation can be visualised in this way and possible measures can be worked out in a targeted manner.

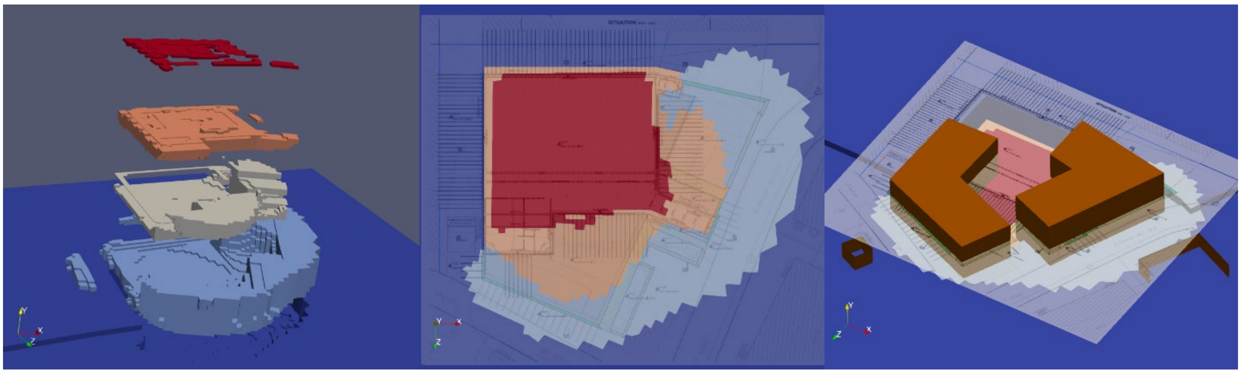


Figure 39. Results from FE calculations for consolidation settlements reduced to concrete value ranges. Spatial delineation of 5 model areas for which the displacements each lie in a specific value range (left), the overlay of the value ranges on the surface with a plan of the excavation pit (centre), and a 3D view with an additional representation of the buildings (right).

6.1.4.4 Findings

In principle, results from FE calculations can be represented using voxel models as well as isovolumes. Both forms have advantages and disadvantages. The following aspects are of interest:

- Geometry: While with isovolumes the geometry of the FE model is adopted directly, a voxel model corresponds to an approximation. In order to represent the geometry of the FE model by voxels, those voxels that lie outside the FE model should not be represented. Marking whether a voxel is inside or outside a model is thus an additional attribute that must be specified for each voxel.

- Attributes: Voxel models define a constant mean value for each attribute per voxel. The smaller the voxel size, the better the model matches the FE model. With the representation via isovolume, however, the attributes are only reproduced over a discrete interval. The smaller the interval and thus the greater the number of isovolumes, the better the agreement between the models. However, a new division into isovolumes must be made for each attribute.

- Amount of data: With voxel geometries, the storage of the attributes is responsible for the memory requirement, while the geometry hardly needs any space. With isovolumes, however, the storage of the geometry is data-intensive, while the attributes are not. In principle, voxel models are inefficient for FE models with widely varying element sizes. Either large elements are represented by many voxels with practically constant attributes, or the accuracy in areas where the FE mesh has been refined is insufficient because the geometry is not represented with sufficient resolution.

Table 2. Comparison of voxels and isovolumes for the presentation of results from FE calculations. Comparison of the advantages and disadvantages of the two approaches for approximating the residuals from FE models with voxel models and isovolumes.

	Voxel	Isovolume
Attribute accuracy	Exact (in the voxel centre)	Depending on the number of intervals
Geometry accuracy	Depending on voxel size	Exact
Memory requirements	Depending on voxel size and number of attributes	Depending on number of intervals and number of attributes
More advantages	• Makes sense with evenly spaced grids	• Useful with few attributes • Visually appealing presentation
Other disadvantages	• Inefficient if many voxels lie outside the FE model	• Complex isovolumes with highly variable attributes (many partial volumes)
Uniform FE grid	Relevant	Irrelevant

6.2 Application to natural hazards

6.2.1 Building protection against permanent landslides

Note: This section is an article published in issue 9 of the SIA journal TEC21 of 25 March 2022 (https://www.espazium.ch/de/aktuelles/GEOL_BIM).

6-8% of Switzerland's surface area is affected by mass movements (BAFU, 2020). The innovation project GEOL_BIM highlights optimisation potentials for the planning and maintenance of building protection measures in the use case "Building protection against permanent ground movements" ("Gebäudeschutz vor permanenten Bodenbewegungen"). Construction projects in landslide areas can benefit from the results.

Permanent landslides (Figure 40) lead to massive damage to buildings due to tilting, twisting and consolidation due to hazards such as increased earth pressure or differential ground movements. Planners are faced with the challenge of counteracting such effects on the supporting structure of a building with suitable structural measures (SIA, 2020, p. 261). The new forms of cooperation in the application of the BIM method (SN EN ISO 19650-1:2018 de, 2018) and the central exchange of information via the digital building model (DBM) support the professionals involved in this.

Figure 40. Photos from the Chratzera landslide report. Crack area of the landslide in Grindelwald (left) and repeatedly adapted garage roof in the village (right).

6.2.1.1 Geology In the digital building model

The innovation project initiated by the Swiss Geologists' Association CHGEOL and co-financed by the Swiss Innovation Promotion Agency Innosuisse poses the question of integrating geology and geotechnics into the application of the BIM method (SN EN ISO 19650-1:2018 de, 2018).

A common and internationally standardised format for data exchange in the construction industry is the Industry Foundation Classes, or IFC for short (SN EN ISO 16739, 2016). However, the currently valid standard is not yet explicitly designed for geological and geotechnical applications. However, the inclusion of geological expertise is central, especially for civil engineering and natural hazard prevention. To map the geology, GEOL_BIM therefore relies on the internationally established conceptual data model GeoSciML 4.1 (OGC, 2017a).

With the help of workflows specially designed for geological use cases, information deemed relevant for landslide areas has been transferred to IFC using GEOL_BIM as an example, taking into account the GeoSciML data model. Figure 41 shows selected results in the BIM viewer and as an illustration using the example of the Chratzera landslide in Grindelwald.

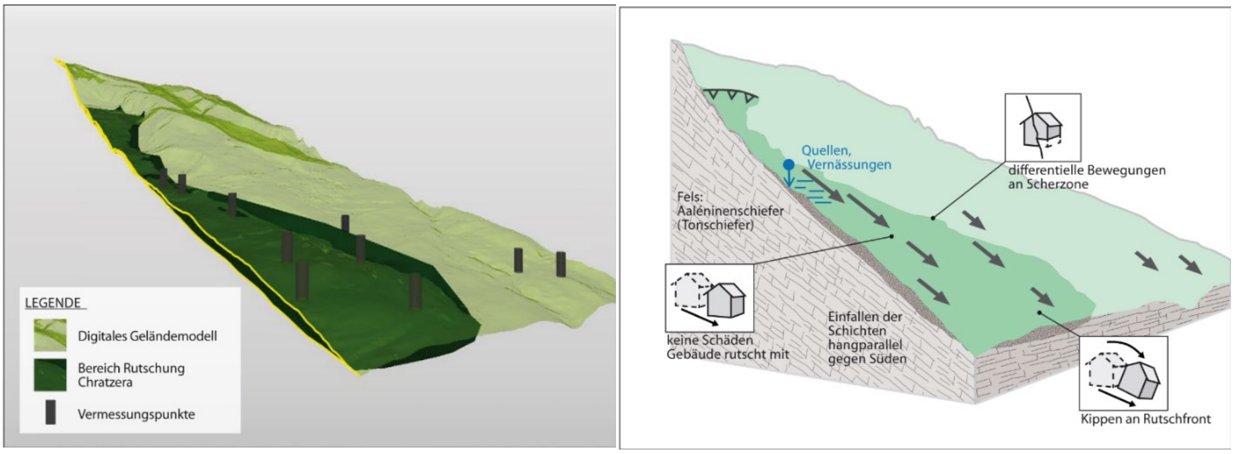


Figure 41. Representations of the Chratzera landslide for cooperation. Sample data in the BIM viewer (left), interpreted block model (right).

6.2.1.2 Risk-optimised planning and management

The application of the BIM method to permanent landslides serves to minimise risks from this natural hazard and should ensure the functionality of a building over its entire lifetime. In order to optimise the flow of information, a process map was developed that describes the relevant issues concerning permanent ground movements as well as the data required for this and the roles of the stakeholders involved for the application of the BIM method (IDM method) (ISO, 2016). This maps the cooperation of the various stakeholders throughout the life cycle of a building (Figure 42).

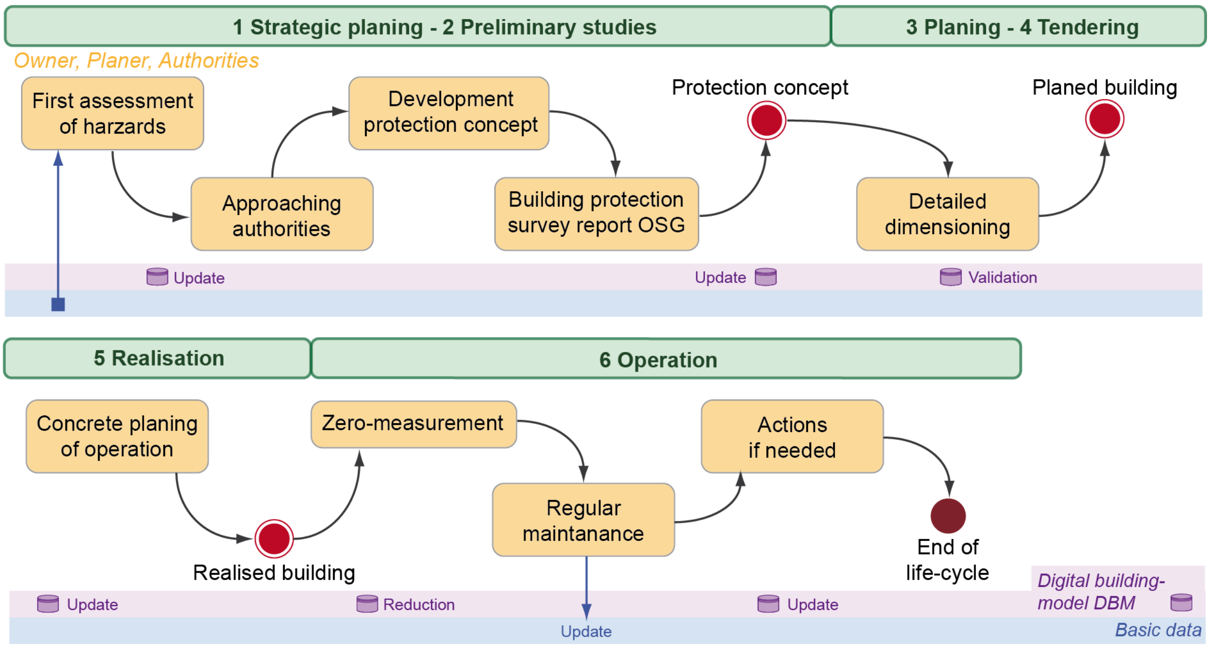


Figure 42. Simplified process map for "permanent landslides". The presentation ranges from the early planning phases to management.

Fundamental to an optimal planning process is a thorough initial hazard assessment at the start of a project. This approach prevents surprises in later project phases and expands the scope for good planning solutions. This is because project changes or subsequently added protective measures can mean considerable additional work and costs for the building owner.

In addition to basic geological data such as geological maps or existing boreholes, the cantonal hazard maps are an essential basis for the clarification of the hazard. With the separation of the landslide surfaces and their attribution with properties of the landslide, they represent an easily accessible and yet information-rich data set that characterises the landslide movement and the resulting impacts on structures. Current hazard maps are available for many settlement areas. In addition, further information such as displacement vectors, inclinometer data, geophysical profiles, hydrogeological data and documented damage may be available on an area-by-area basis.

The elaborated process map also provides for maintenance measures. The prospect of less damage should motivate the building owner to carry out a regular, for example annual or biennial, inspection of the building object. Depending on the hazard pattern and movement rates, this can be done visually or by means of position sensors and measuring marks. A minimal approach could be that a precise zero measurement of the building location (coordinates, angle of the outer walls) is carried out during commissioning. If tilting, twisting or consolidation is suspected, this zero measurement later serves as a reference value.

6.2.1.3 Valuable information from maintenance and damage reports

Carefully planned and executed maintenance and damage reports can provide new information for prevention. Findings indicating landslide system changes could trigger an event-related revision of the hazard map and area-specific investigations. In this way, the renewal of the hazard base could be prioritised on the basis of evidence, and construction projects could benefit from the more up-to-date and possibly more meaningful data. The improved data basis is used not only for planning but also for the subsequent validation of remediation measures, such as drainage, to slow down landslide movements.

GEOL_BIM thus takes the first steps towards digital continuity of geological information for collaboration with BIM and enables communication without disruptions across different technical expertise. A field of new possibilities opens up for dealing with the uncertainties and risks of the subsurface. The planning and implementation of protective measures and maintenance can be optimised, particularly with regard to the effects on the load-bearing structures of buildings and infrastructure structures.

6.2.2 Landslides in the digital building model

6.2.2.1 Project

The Brienz/Brienzauls landslide in the canton of Graubünden has been on everyone's lips since 2017 at the latest, when landslide movements accelerated sharply to currently 1-2 m/year in the lower (populated) part and 3-7 m/year in the upper part. Numerous landslide phenomena of this major slope movements are visible to the naked eye in the southern flank of Piz Linard (Figure 43 & Figure 44). In the middle of the slide mass is the village of Brienz with just under 100 inhabitants as well as traffic routes (cantonal roads, RhB line). Due to the considerable damage potential, the aim is to achieve a slowing down of the landslide movements as quickly as possible with technical measures. The evaluation of up to 340 m deep exploratory boreholes through the slide mass has revealed that increased water pressures in the subsurface could be the main cause of the slide movements. By means of an exploratory tunnel located below the landslide mass, a pilot test is now planned to investigate and test the drainability of the subsurface with the tunnel excavation and targeted boreholes. The exploratory tunnel has been under construction since the beginning of September 2021 (status of tunnelling on 21 January 2022: 313.5 m). If the effect is positive, the exploratory tunnel could be extended and converted into a drainage tunnel, so that one day the sliding movements will slow down and further damage to the infrastructure will be avoided.

Figure 43. View of Brienz landslide from the south with the village of Brienz/Brienzauls GR.

Figure 44. Damage to the foundation of a barn due to differential deformations.

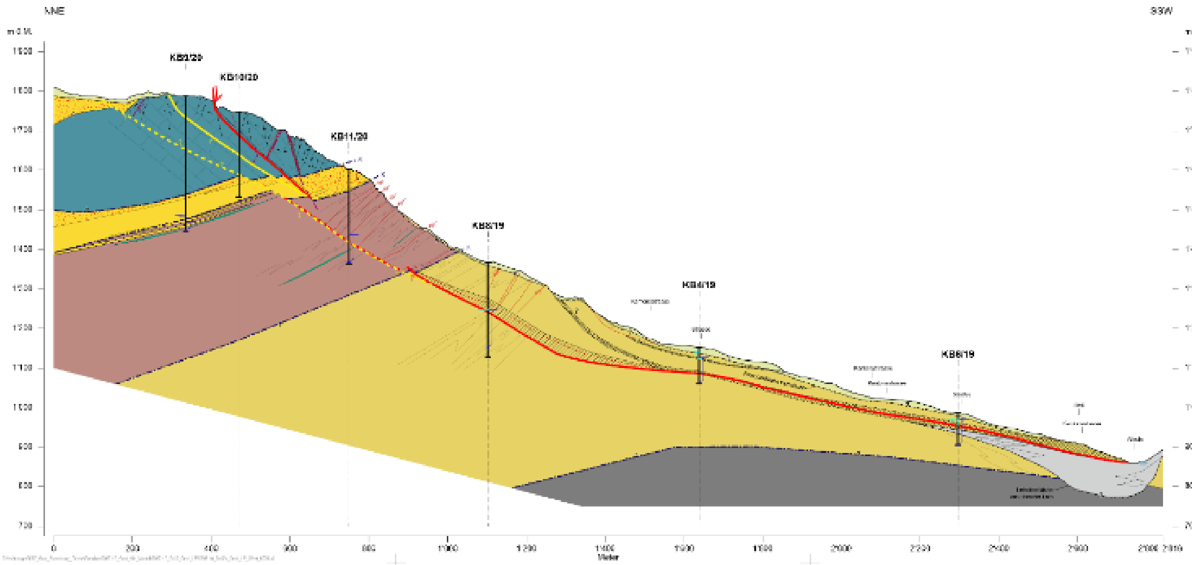


Figure 45. Longitudinal geological profile of the Brienz landslide. Longitudinal profile west Brienz/Brienzauls GR with geological units(coloured), boreholes (black) and slide surface (red).

6.2.2.2 Methodology

Use case 3 aims to support the transfer of information on hazards and intensities from gravitational processes into BIM software and thus make them more usable over the entire life cycle of a structure. The monitoring data during the operational phase of the structure are of central importance in order to enable the planning of possible rehabilitation measures in the vicinity of the structure as well as preventive maintenance work. The measurement data can be used to trace mass displacements from the operational phase back to the original geological model.
The Brienz/Brienzauls landslide is ideally suited as a study object because of the high density of soundings, geophysical, hydrogeological, hydraulic and geotechnical measurement data and also because of the ongoing clarifications regarding technical measures to reduce the movements. The following questions were decisive for use case 3:

- Which geotechnical parameters or attributes of a sliding surface are relevant for the planning, construction and operation phases, or must be represented in a BIM model?
- How are the boundary surfaces, which are triangular meshes, transferred from the GeoModeller program to the IFC format?
- How does the presentation of geological data in BIM viewers promote the understanding of non-geologists?

The landslide horizon detected in the exploratory boreholes and partly also in geophysical data was interpolated in the 3D modelling program GeoModeller (Intrepid Geophysics) to form a continuous slide surface. The resulting triangle mesh was exported by GeoModeller into both TS and DXF format for testing purposes. Before that, the exported files were checked by the CHGEOL project team for their convertibility into IFC format. The interoperability of GeoModeller with BIM was successfully tested. Now, using the gf2ifc adapter and the EXCEL transfer schema, the slide surfaces were transferred to IFC format.
The transferred IFC files of the slide surface were characterised with geological-geotechnical attributes in the EXCEL transfer schema. In addition to the slide surface, the swisstopo terrain model was imported as an xyz-ASCII file into the Cloudcompare program (freeware) and saved as an STL file using 2.5D triangulation. These files were also transferred into IFC format, again via gf2ifc adapter and EXCEL transfer scheme. Subsequently, the boreholes were transferred to IFC format via the bhl2ifc adapter using the Excel transfer schema and displayed.
The exploratory tunnel was characterised by means of a circular tunnel cross-section via bhl2ifc adapter (as a horizontal large borehole). To illustrate the state of advance, a larger, colour-coded cylinder was placed over the tunnel tube at the relevant point.
The slide surface, ground surface, boreholes and exploratory tunnel were combined into a project in the Solibri program and saved as an SMC file.

6.2.2.3 Results

Attributes characterisation slide surface
The geotechnical parameters that BTG and von Moos considered important or indispensable for characterising a slide surface are listed in Table 8. The list is not exhaustive.

Table 3. Geotechnical parameters for the slide surface of the Brienz landslide.

Specialised field	Characterisation/attribute	Unit	Data type	Appropriate number ranges, limit values; intervals
Hydrogeology	Water level in the borehole	mH_2O	float	[0, 1000]
	Aquifer type	[-]	Text	Unconsolidated rock (slope/groundwater), rock: (fissure/karst water)
	Permeability / permeability k-value	[m/s]	float	[10^{-1},10^{-13}], logarithm of 10
	Water flow Q	[m^3/s]	float	[0, 1000]
	Mineralisation / Water type / Conductivity	[µS/cm]	float	[0, 300, 600, 900, 1200]
Geology/geotechnics	Lithology	[-]	text	Geological description
	Type of lithology (unconsolidated rock or bedrock)	[-]	boolean	Yes/No
	Inclination / inclination direction parting planes (S, S_0, K, S_t)	[°]	integer	[0-90/0-360]
	Spacing parting planes	[m]	float	[0, 20]
	Length parting planes	[m]	float	[0, 100]
	Water content of unconsolidated rock	[%] H_2O	Integer	[0, 100]
	Friction angle rock formation or	[°]	integer	[0, 50]
	Friction angle parting plane or	[°]	integer	[0, 50]
	Cohesion rock formation or unconsolidated rock	[MN/m^2]	integer	[0, 50]
	Cohesion interface or matrix	[MN/m^2]	integer	[0, 50]
	Compressive strength	[MN/m^2]	integer	[0, 100]
	Modulus of elasticity E	[GPa]	integer	[0, 100]
	Bulk density γ rock or unconsolidated rock	[kN/m^3]	integer / float	[0, 100]

	Z-value	[-]	integer	[1, 2, 3, 4]
	Degree of caciritisation	[-]	integer	[1, 2, 3, 4]
	RQD value	[%]	integer	[0, 100]
	Alkali aggregate reaction (AAR)	[-]	integer	[….]
	Abrasiveness (proportion of	[%] SiO_2	integer	[0, 100]
	Swelling potential rock (according to SIA 199)	[-]	Text	low, medium, high
Slide parameters	Slide velocity in depth x m	[m/y]	float	[0, 10]
	Direction of inclination movement / inclination direction in depth x m	[°]	integer	[0-90/0-360]
	Deformation behaviour at depth x m	[-]	Text	Ductile, brittle
	Location of deformation at depth x m	[-]	Text	Slide surface, parting plane, diffuse (no slide/parting plane)
	Large-scale slide behaviour	[-]	Text	Rotational, translational sliding, toppling

BIM model Brienz landslide
The BIM model of the Brienz landslide is displayed in the Solibri viewer. By selecting cutting planes, the desired profile sections can be selected and displayed in the model – analogous to GeoModeller (Figure 46 – Figure 48).

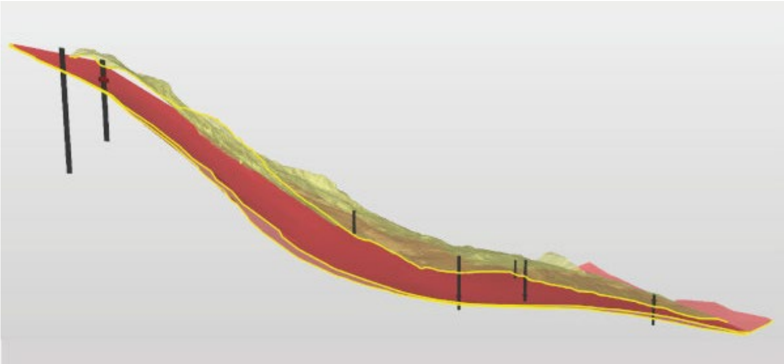


Figure 46. Longitudinal profile of the Brienz landslide from the BIM viewer Solibri.

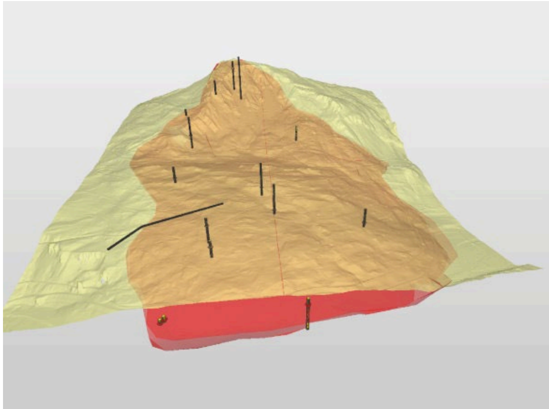


Figure 47. Top view of the Brienz landslide in the BIM viewer Solibri. The figure shows the slide perimeter (orange), sliding surface (red), terrain model (yellow), exploratory boreholes (black) and exploratory tunnels (black).

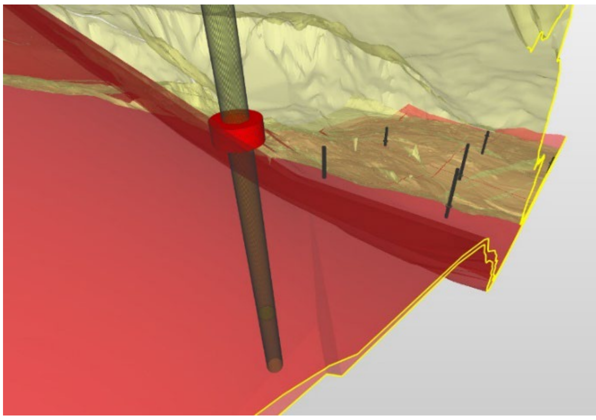


Figure 48. Side view of the Brienz landslide in the BIM viewer Solibri. The figure shows the slide body with exploratory boreholes and indexed slide surface (red ring).

6.2.2.4 Findings

The BIM model Brienz was presented and discussed internally and externally with the project participants of the Brienz landslide (specialist offices of the Canton of Grisons). It was revealed that the project geologist was able to convey their information and assessments better and more sustainably to the various project participants with the presentation of the BIM model Brienz. The geologists' own imagery, the so-called "mental cinema", thus becomes more tangible and understandable for planners from other disciplines as well as for the client. The common mental cinema is also made possible thanks to the reduction to the essential data or the limitation to interpreted data and simplifies the cooperation with the other project participants.

Nevertheless, a rethink is needed among the draughtsmen, surveyors, engineers and geologists involved, as the following effective planning procedure for the Brienz exploratory tunnel shows. Not only in the case of the Brienz exploratory tunnel, but also traditional tunnels and galleries for power plants and transport infrastructure are still planned, drawn and also visualised using CAD software (e.g. AutoCAD). Corresponding CAD formats must also be transferred to the IFC format in order to be analysed together with the geological data in digital building models. The problem is that the geologists in the offices rarely work with CAD software, but instead use drawing software (Adobe-Illustrator, CorelDraw, Inkscape, etc.). Exporting e.g. profile sections from Adobe Illustrator into a georeferenced format does not work. For this reason, it is important to enter the geological basics from the beginning, if possible, in 3D, and in a program that also supports the appropriate data exports for conversion into IFC format. All relevant data for the Brienz landslide were imported into the GeoModeller program and formed the basis for further investigations. Among other things, the suitable course of the axis of the exploratory tunnel from a geological-geotechnical point of view was created with reference to the sliding surface using 2D profiles along the tunnel axis from the GeoModeller. The exported 2D profiles were further processed with drawing software and delivered to the tunnel planners/contractors in the form of PDFs in digital and print form. The latter step involving a break in digital planning (digital data to PDF/print documents) should be avoided in the future. A first measure or learning effect could therefore be to rely on BIM or geological data in IFC format in the further course of the project.
The further planning of possible variants of the exploratory tunnel or parallel planning of the drainage tunnel should continue to be advanced in the GeoModeller. Unlike in the past, the relevant information from GeoModeller (layer course, sliding surface, etc.) should be transferred directly to IFC format without the need for drawing software. The geo-IFC files and those of the tunnel engineer are combined and visualised in a BIM model. The planned variant study for the drainage tunnel can now be carried out in the BIM viewer independently of the software. This requires a suitable BIM viewer with the ability to create any sections with integrated length and height information, which is currently not possible with Solibri Anywhere, for example. Furthermore, an interactive measurement function of distance (e.g. distance of tunnel to sliding surface) similar to the corresponding functionality in a GIS program is desirable. Last but not least, the extraction of spatial coordinates of an important point (e.g. future drilling site) is indispensable to make the step from a purely presentational BIM model to a working BIM model. In practice, the first complex BIM projects will show how many tools are really necessary in a BIM viewer or whether important planning steps are not carried out independently in the 3D model software. The BIM viewer must first and foremost be a powerful viewer and not merely a glorified 3D GIS program. In this sense, an editing or drawing function (similar to shapefile creation in GIS) would probably have overshot the mark.

The BIM model of the Brienz landslide shows the spatial position and geometry of the sliding surface and the thickness of the landslide as modelled in the geomodel. In the course of our own validation and presentation of the Brienz BIM model, it became apparent that a few technical aspects require more detailed discussion. The technical aspects are listed in Table 9.

6.2.2.5 Outlook/next steps

As explained in the previous Section 5.5.4.4, the further procedure in the Brienz landslide project will be based on a stronger integration of the data transfer into the IFC format and the input into the BIM model. In the first phase, important experience in digital cooperation is to be gained. Whether conventional planning will continue to be used in parallel to purely digital planning is still open. On the geology side, a lot probably depends on how easy it is to handle the adapters, EXCEL schemas and, not least, the BIM viewer. In particular, the possibility of creating geological sections must be ensured, which to date is only possible using existing line elements. Other features such as measurement functions (length, height) or determination of spatial coordinates are of eminent importance from a practical point of view in order to enable the use of BIM models in daily project work. In our view, a close exchange between practice and research and development – similar to what has happened in this GEOL-BIM research project – is not only beneficial but also necessary for BIM.

Table 4. Technical aspects and learning effects on the BIM model Brienz

Aspect	BTG/vM experience	Problem solution proposal
Cutting planes	Cutting planes can only be selected along existing geometries (e.g. axis of exploratory tunnel). Random cuts in the middle of the slide body are not selectable without preliminary work.	Create a systematic grid with main directions parallel and orthogonal to the landslide A rotatable, adaptable "auxiliary grid" for the flexible creation of cuts would be ideal.
Distorted, not to scale representation for the purpose of improving visibility (boreholes, borehole intervals (e.g. sliding surface))	Indispensable for the presentation and for the purpose of quickly recording the data situation, but obstructive in detail or at large zoom levels.	Maintaining the distorted data – contrary to the BIM philosophy of not distorting. One way out is to use the distorted representation to show the uncertainty of the geological-geotechnical conditions (e.g. 1-sigma envelope).
Approximate horseshoe-shaped tunnel cross-section with circular tunnel cross-section	The 2D geometry of the exploratory tunnel cannot be accurately reproduced and consequently neither can the conditions encountered during the face survey. Due to the approximation to a circle, the conditions of the geology and interfaces cannot simply be transferred 1:1 in individual cases or in the case of delicate hazard patterns (collapse, instabilities, etc.).	Approximation of elliptical tunnel geometries by means of an envelope of two stacked circles with different radii.
Large amounts of data to be processed with spatially large geometries and high spatial resolution	Long processing times (import/export of grid models) for the 4 km^2 perimeter of the Brienz landslide, good hardware required to work efficiently in Solibri	Limited to good raster resolutions in the vicinity of infrastructure/project. Streamline project files where possible (avoid unnecessary data in IFC format)
Clarity of the geodata	High spatial density of geodata (boreholes, geodesy, possibly geophysics) may impede clarity.	The interpreted geological data – the geological model – with layer courses, slide planes, faults, etc. are imported into the BIM model and displayed. For the purpose of sensitising the quality of the geological model, the boreholes can be added. It is important to note that the BIM model is not an interpretation software, but is used for the interactive exchange of data.

7 Conclusion

Geologists provide concrete recommendations for dealing with the underground. Based on the premise that a total system is completely determined by the sum of its individual parts, the approach is reductionist in nature. Similar to a medical doctor who cannot examine every cell of the human body before treatment, the geologist also faces the challenge of not being able to fully analyse their complex object of study – the underground – first. Instead, it is often unavoidable to make a recommendation based on incomplete information and to the best of one's knowledge and belief. The ways of thinking and approaching applied geology as a scientific discipline are therefore academic in nature. In highly individual and case-specific studies, the causal relationships of the concrete geology on site are studied in detail in order to then arrive at a defensible recommendation, taking all uncertainties into account. Solid basic knowledge in all natural sciences, creativity and the freedom to analyse every observed geological constellation with an open mind and without any methodological restrictions is the foundation of the geological working method.

However, there is also the desire to be able to transfer geological results to the party seeking of such information in a structured and machine-readable way. For the supplier, the aim is to make the achievements of geological work tangible for the recipients of the information and to be able to communicate the geological expertise in a targeted manner. The prerequisite for such an exchange of information is a common language and a harmonised exchange of information. In other words, it is helpful to always transmit information in the same way if it is to be visualisable with the recipient's tools or even analysable in an automated way. GEOL_BIM has set itself the goal of laying the foundation for such a harmonised exchange of information. For this purpose, the project evaluates potentially suitable conceptual data models. With the Geoscience Markup Language (GeoSciML), the Open Geospatial Consortium (OGC) has succeeded in creating an open and widely applicable conceptual data model of geology. Based on GeoSciML, GEOL_BIM shows that geological information structured in this way is also suitable for collaboration in larger construction projects. In a hardly regulated discipline such as geology, the common language underlying such models is currently poorly formalised. It may even be that strict formalisation is completely at odds with the academic self-conception of the discipline. In contrast to other disciplines such as the more standards-affine engineering sciences, there have been few initiatives attempting to lay a common language base for applied geology. GEOL_BIM raises awareness of the need for a common language for applied geology and a consensus developed within the discipline of what information needs to be transferred for collaboration in construction projects.

7.1 Appraisal of target achievement

The overall project goal of GEOL_BIM is the integration of geology into the application of the BIM method. This overall objective is to be achieved with a focus on information exchange through the development of interface specifications and tools, as can be seen from the project objectives listed in Section 2.1. In the following, the defined project objectives are taken up, assessed and discussed against the achieved project results.

7.1.1 Overarching goals

Design of semantic and conceptual data models, workflows, guidelines, standards and best practices

With the transfer and reference model, GEOL_BIM provides a conceptual basis on which the elementary geological and geotechnical information can be exchanged in a structured way. These conceptual data models form a solid foundation for a common understanding and stronger harmonisation in the future within geology, but also between geology and other construction and engineering disciplines.
Tools are developed that are based on these data models and with which different practical examples were tested to evaluate possible applications (see Section 6). As these are only individual applications from very different use cases so far, it is not yet possible to speak of best practices. The tools now available, especially the web application, allow a low-threshold entry into the preparation of geological information for construction projects, so that best practices can develop from this.
What is still challenging is the common understanding and standardisation at the semantic level. Within the framework of the project, it was not possible to develop a common definition among all project participants for all open questions. However, the support of the international standard GeoSciML makes it possible to build on an already well-developed basis for future discourses.
This goal was achieved at the level of the conceptual data model. In terms of guidelines and standards, the goal was only partially achieved.

Precise definition of national needs for the adaptation of international standards to Switzerland's country-specific requirements
See explanations in the following Section 7.1.2. As described in the sections below, this goal has been worked on very comprehensively and is therefore also assessed as achieved.

Development of implementation concepts and prototypical realisations of manufacturer-independent, system-neutral and open interfaces for the integration of geology into the BIM method
The developed interface is based technically and conceptually on the international, open standard GeoSciML. In addition, transformation rules are defined in the open, international standard IFC and tools for the transformation are developed and validated. The data of the practice partners used for the validation originate from different source systems and were validated with different BIM viewers.
This objective has been extensively addressed with the 6 case studies in Section 6 and has been assessed as achieved.

7.1.2 Technical goals

Importing geological information in commercially available BIM software
The transfer model GEOL_BIM provides a technical interface through which geological information can be transferred to IFC and imported into common BIM software. This technical interface is generally defined so that different representations of geological models can be transferred. Explicitly supported are 3D models (layer model and voxel model), profile sections, boreholes and voxels.

Enabling quantity take-offs
The transfer model GEOL_BIM is based on an object-oriented, conceptual data model and is strongly oriented towards the international standard GeoSciML. The essential aspects of geology can thus be described technically in the transfer model and also can also be transferred into the IFC format. The relevant geological information can thus also be made available in the BIM software and can be evaluated there with the existing functionalities, e.g. with regard to the extraction of quantities.
The technical feasibility of quantity take-offs is thus given. A practical validation with a concrete practical project could not be carried out, as no corresponding concrete tasks for machine evaluations of geological information in the BIM context were introduced. In general, it has been shown that the current requirements from practice are still focussed on visual analysis. Machine-based and automatable evaluations are still hardly used. This is probably due to the fact that there is still little experience in dealing with digitally available data, that is structured to facilitate machine-based evaluations.

Transfer of uncertainties associated with geological models into BIM software
Two solutions are presented with which information on uncertainties of geological information can be dealt with (attributive description, geometric description, see Section 4.4). In principle, both solutions can be represented or implemented in a simple way with the GEOL_BIM transfer model. However, the application of the geometric approach with the current transfer model will be limiting, especially in the evaluation, because the dependencies of the related geometries cannot be mapped.
Both solutions can only be demonstrated theoretically in the project. Effective implementation and validation are not possible due to a lack of concrete practical data. See also supplementary explanations in the following section.

Data exchange with IFC including Switzerland-specific requirements and compatibility with IFC version 5
The exchange of geological data with the IFC standard is shown conceptually and specified with a submodel definition. With the developed adapters, these conceptual definitions are implemented and geological data can be transferred into the IFC format and made available in the BIM software. The features of the adapters were validated with real-world data in all processed use cases.
Based on the international standard GeoSciML, there are only a few Switzerland-specific requirements that can be mapped with the extension mechanisms provided by IFC. In particular, GEOL_BIM specifies six user-defined PropertySets (see Section 4.2). Nationally specific requirements also arise, especially in the area of value range definitions of classification systems.
The submodel GEOL_BIM shown is defined for IFC versions 4 and 4.3. Version 4.3 is currently about to be released and for the first time contains specific data structures for mapping geological information. The first explicit mapping of geological information was originally planned for version 5, but was then integrated into version 4.3, as were all areas related to infrastructure construction. For this reason, version 4.3 and not version 5 is supported in GEOL_BIM. It will still take some time until version 4.3 is established

and distributed in most software products and in the industry, which is why a sub-model for version 4 is also shown in GEOL_BIM, which can be used immediately.

Providing machine-readable information requirements with mvdXML
Based on the IFC sub-model, the information requirements are also specified in machine-readable form. For this purpose, the new standard Information Delivery Specification (IDS) (buildingSmart International, n.d.) is used instead of the originally intended standard mvdXML. IDS is currently being developed by buildingSmart and will be released in a first version in spring 2022. Compared to mvdXML, IDS should enable a simpler definition of information requirements and thus become better established in software products.
Remark: The definition of the information requirements of GEOL_BIM with IDS is planned for April 2022, when a stable version of IDS will be available.

Validated prototypical implementation of the solution concepts in 3 use cases
The conceptual data model is implemented with a concrete interface specification at the logical level. Simple standard products are used for this purpose (Excel, established CAD formats), so that there is as low a hurdle as possible for their use. Based on the interface specification, various adapters have been developed with which geological data can be transformed into the IFC format. The resulting IFC data can be imported and processed in common BIM tools. The interface and the adapters are validated with different data from the project partners.
In addition to the original planning, an easy-to-use web application will be provided so that the adapters can also be used without local installation and thus with a low technical hurdle.

7.2 Lessons-learned

GEOL_BIM addresses the issue of integrating geology into digital collaboration methods for construction projects. Based on case studies in the three application areas of tunnelling, subsoil and natural hazards, using the example of permanent ground movements, the requirements for information exchange were investigated. Many commonalities between the application areas investigated could be identified and brought together in a proposal for a common data model for information exchange. With the prototypical implementation of the data model in three scripts written in the Python programming language, the transfer of geological results to IFC was successful. Bringing all three scripts together in a web application that can be used without programming knowledge shows that the methodologies developed can be made accessible to a wider audience.

7.2.1 Case studies

GEOL_BIM has succeeded in analysing several case studies from the three very different application areas of tunnelling, subsoil and natural hazards (permanent ground movements) with regard to their information requirements for cooperation in construction projects. Despite the diversity of very heterogeneous case studies, it was possible to define common requirements for the exchange of information. The basic needs include the structured transfer of borehole information, as well as information linked to geological structures, units or voxel models.

In construction projects, the client is required to define as clearly as possible which objectives are to be achieved with the information to be provided. In consultation with the supplier, it is then necessary to work out early in the project which information is required in which level of detail to achieve the objectives (SN EN ISO 19650-1:2018 and SN EN ISO 19650-2:2018). In GEOL_BIM, the supplier view was studied more closely. For the construction process as a whole, however, the information requirements of the client are just as important. For successful cooperation, the supplier needs to understand how their information is used after delivery and the client needs the competence to communicate their information requirements clearly and purposefully.

Within the framework of GEOL_BIM, it was not possible to track the entire flow of information in a construction project across the design, planning and implementation phases, if only because of the limited project duration. The available information and documents on the practical projects have often been selected for use in GEOL_BIM from a retrospective perspective. This information was extremely helpful for GEOL_BIM, but it only provides a selective and thus incomplete picture of the entire construction process.

GEOL_BIM has deliberately focused on selected case studies. The data model developed from the practical projects examined served as the basis for the exemplary and detailed information exchange with the GEOL_BIM interface. The conceptual data model was deliberately designed with extensibility in mind. Based not least on the technical breadth of the underlying GeoSciML, it can be assumed that the methodology can be transferred to other use cases. Whether all conceivable use cases can be mapped remains open.

The technical model developed in GEOL_BIM is also extremely simplified. It remains to be evaluated whether more complex use cases require significantly more detailed subject models. Plenty of topics for discussion remain for the common language and the concrete implementation of detailed domain-specific models.

7.2.2 Heterogeneity of geological approaches

What was striking and unexpected for many of the project supporters directly involved in GEOL_BIM was the heterogeneity of the methods (acquisition, processing and evaluation of data, but also fundamental understandings of processes and definitions of terms) and tools with which geological questions are answered today. A homogeneity in the understanding of processes could be found most strongly within the areas of natural hazards and tunnelling.
Despite the heterogeneity, it was possible to identify common requirements for the exchange of information and to develop concrete proposals for solutions for transfer to IFC.
The interface specifications and tools provided with GEOL_BIM can be used independently of the applied, versatile geological methods. A certain heterogeneity of domain-specific methods is necessary and in principle to be supported. GEOL_BIM only defines the structure of the geological information to be transferred to the construction projects.

A key factor in achieving this uniform structure is the reliance on the GeoSciML data model, which has allowed us to build on existing principles and concepts. A complete redefinition of a data model for geology within the project was not possible due to the heterogeneity of the different views and understandings. At the same time, however, the reliance on GeoSciML is also a critical factor for establishing the results of GEOL_BIM in practice. This is because it has become apparent that the concepts of GeoSciML are hardly known and not established in Swiss practice itself. However, the use of the results of GEOL_BIM requires a certain degree of examination and competence building with regard to these concepts and principles. Thanks to deliberate simplifications in the GEOL_BIM transfer model and the tools provided; however, low-threshold access and entry should be relatively easy for interested parties.
On the basis of the conceptual data model and the homogeneously structured data based on it, terminology, methods and processes can be aligned in the future and harmonised and standardised to a greater extent. This requires an exchange and discourse between the parties involved, which can be supported e.g. by CHGEOL and swisstopo.

The heterogeneity of the methods is also reflected in the use of specialist software for geology. A large number of different products are in use, with no real "market leaders" emerging. This is one of the reasons why the project refrained from implementing specific adapters for individual geology software products.

7.2.3 Data model for geology

It is a challenge to choose the structure (classes and relationships) of a flexibly applicable conceptual exchange model in such a way that the result can be used sustainably and widely without restricting the users too much in their specific workflow. It has been shown that simple application examples ("simple" in terms of geometries, attributes, processes, visualisation, analysis requirements) are conducive to building a common understanding. An exchange model for cooperation in construction projects that claims to be representative of the totality of all geological topics would have to take into account further topics of geology in the future. Particular attention should be paid to the interdisciplinary topics of hydrogeology. Nevertheless, it has been possible to develop a data model for the Swiss geology sector based on an internationally recognised data model (GeoSciML) and local adaptations. The GEOL_BIM data model is aligned with the borehole data model and the geology data model of the State Geological Survey and has specific extensions that were contributed by the practice partners in the innovation project. Nevertheless, the data model is very generic and it still allows for project-specific adaptations.

The GEOL_BIM data model is an important step towards a more standardised way of working and lays the foundation for the digitisation of geology. Building on the data model, new digital processes can be developed which, on the one hand, enable simpler processing chains with fewer media breaks and, on the other hand, also offer new possibilities in the evaluation of the information.

The tools based on the GEOL_BIM transfer model provide a low-threshold introduction to digital processing and uniformly structured storage of geological information. A first step towards digital working can thus be taken.

The transfer model is currently implemented with relatively primitive technical standards (Excel, CAD) and thus not designed for the exchange of stronger and more intelligently connected information. When structured, object-oriented management of geological information has become established in the future, a revision of the transfer model is necessary so that it can also represent more complicated geological information. This includes, for example, references between the individual geological layers or models, references to measurement data and measurement campaigns, to inaccuracy information, etc. The possibilities for this are already shown and defined in the GeoSciML+ reference model. Thus, no new concepts have to be developed for the enhancement of the transfer model, but "only" possible simplifications compared to the reference model have to be considered.
When mapping mutual references, it is no longer possible to primarily use manually edited formats such as Excel, instead more structured, machine-edited formats must be used. These higher-quality transfer models would then also have to be generated from the geology tools via automated export adapters.

For the future maintenance and further development of the GEOL_BIM data models, two points are particularly worth highlighting.

- Generic properties: The generic approach of the data model allows geological properties to be freely defined. This flexibility was deliberately chosen in order to be able to support project-specific requirements in an uncomplicated way on the one hand, and on the other hand not to force standardisation in the short and medium term (which would have required a longer technical discussion and decision-making process). Nevertheless, the definition of standard attributes is intended to harmonise the geological properties used (see Section 4.1.3.1). Maintaining these standard attributes is therefore an important task and is to be understood as part of the maintenance of the data model.

- Value lists: Part of the heterogeneity is evident in the use of value lists, especially for classifications. Within the framework of the GEOL_BIM project, the basic structures were defined with the data model, without, however, any in-depth technical analysis or discussion regarding concrete values of all value lists. The technical coordination and harmonisation of value lists is an important task in order to achieve harmonisation of data in the long term.

With the GEOL_BIM transfer model, the basic structures for the exchange of information are defined. Nevertheless, for the exchange of information in a concrete project, the specific information requirements must be determined individually, because the transfer model defines the possible framework. The relevant areas must be determined on a project-specific basis, following the individual objectives. Ideally, this should be determined by the parties that use the geological information (information providers according to (SN EN ISO 19650-1:2018 de, 2018)).
The specification of the information requirements also includes, in particular, the exact specification of the geological properties to be exchanged on the basis of the standard attributes. For the specification of the project-specific information requirements, the IDS specification of GEOL_BIM can be used as a basis. The use of supporting tools is recommended.

7.2.4 **Geometry requirements**

IFC offers a wide range of options for mapping different types of geometry or different geometric representations. The possibilities for mapping body geometries in IFC can be divided into implicit and explicit procedures. If the geological expert software does not support more complex geometry types – such as the Boundary Representations (B-Rep) commonly used in IFC (Reference Fundamental Report BIM Method, Section 6.1 (Schneider et al., 2021, in German) – then triangular or polygonal meshes can be used. GEOL_BIM thus achieves a solution for the transfer of geometries that is as flexible as possible, preferably with open formats for export from geological expert software.

Many products commonly used in geology allow geometries to be defined as lines or points, but to be displayed in other geometric forms, e.g. as tubes or cuboids, for visualisation and analysis purposes. As this feature is missing in the BIM viewers available today, these data must first be explicitly converted into the explicit geometry definitions before they can subsequently be transformed into IFC and displayed in the BIM viewer (e.g. borehole: conversion of line to tube; voxel: conversion of point to cuboid; cf. Section 3.2 and 4.1). These geometric conversion steps are performed in GEOL_BIM by the developed adapters.

Some geological software products make it possible not only to attribute information to individual surfaces, but also to provide the vertices and edges from which the surfaces are constructed with more specific information (attribution of individual geometry elements). However, the possibilities to export these attributed geometries into open exchange formats are very limited in the geological software products. Furthermore, there is no direct way to transfer such data into the IFC format. These limitations, as well as the limited amount of concrete sample data of this kind (from the advisory group), led to the decision not to pursue attaching attributes to vertices or edges in the project.

7.2.5 Diversity of geological software solutions

A variety of different software products from different manufacturers and in all price categories are available for the preparation of geological results. The different solutions vary greatly in their ability to export the results into file formats that can be read by other software products. With a focus on OBJ, STL, DXF and TS (TSurf), GEOL_BIM has succeeded in exporting from all the software packages used in the case studies into an open format and integrating the exported geometries into a digital building model.

The fact that some software packages on the market allow the export of geometries in only a few or no open formats is a hindrance to data exchange. If converting the data is essential, this can result in additional work, the need for additional software and thus increased costs. Another complicating factor is that the flexible attribution of geometries, i.e. the arbitrary assignment of properties to geometric bodies, is sometimes only possible to a very limited extent in geological 3D software. As a consequence, it may indeed make sense that information required for collaboration is kept outside the 3D modelling software. Even if the export of all geometries including their attribution is successful, differences in the structures of the export and the target structure can make the further use of the data more difficult and again generate additional work and costs.

Software manufacturers do not always guarantee that all attributes can be exported together with the geometries. This point hinders digital continuity.

Recommendation
Objects must be uniquely identified, information management possible centrally in one place, with reference to Object identifier.

7.2.6 Mapping of the geology in IFC

In the official versions of IFC published so far, dedicated structures (entities) for mapping geology are missing. The geological information can nevertheless be transferred to IFC by "misusing" structures not intended for this purpose, and can also be visualised and evaluated there. For correct use, however, explicit additional agreements and conventions are needed so that the semantics of the information can be correctly recognised and interpreted. To preserve the value of the information in the long term and to increase efficiency, generally valid and well-known, semantically precise definitions are required. With the new version 4.3 of IFC, which will be released soon, specific structures for geology will be provided for the first time. A mapping between GeoSciML and IFC 4.3 is shown by GEOL_BIM. This reveals that the structures defined with IFC are very rudimentary and only allow a little precise and little balanced technical representation of the geology. As for the current possibilities of the transfer model GEOL_BIM, however, a target-oriented transformation according to IFC can still be shown, so that the relevant geological information can be provided in digital building models in a semantically largely self-explanatory way. However, for more complicated relationships, such as those that occur in the reference model or in GeoSciML, the possibilities of IFC are limiting, or the current implementations of IFC are limiting. This finding primarily refers to the possibility of mapping relationships between individual objects, which are important for in-depth analyses and interpretations of geological information. The representation of relationships between objects is possible in principle in IFC, but is only insufficiently supported by today's software products.

7.2.7 Geological data in the BIM viewer

Using numerous case studies as examples, the GEOL_BIM project has succeeded in exporting various results from geological expert tools into open exchange formats and transferring them to IFC for communication via digital building models. The large spatial extent of geological models could be successfully tested with the approach of georeferencing in IFC. The chosen best-practice approach for georeferencing (LoGeoRef) enables the implementation of larger linear projects as well as smaller local projects. With the application example of the 2nd tube of the Gotthard road tunnel, we were able to test a larger linear tunnel project of almost 17 km length with a highly simplified model.

The strengths of geological 3D software lie in the efficient representation of large amounts of data and enable spatial queries based on freely selectable object properties. To make the multitude of overlapping and space-filling properties of the substrate visually tangible, these tools rely on dynamic colouring and flexible options for cutting through the model. In most of the currently available BIM viewers, these features are missing or only available in a very simplified way. However, these features are necessary for analysing the geological information.
The investigation of 7 different BIM viewers has shown that there are some limitations with regard to the large amounts of data and the features. Performance problems have occurred especially with very detailed triangular meshes. With larger voxel models or a high number of attributes in voxel models, performance problems can also occur.
The generation of cross sections for simple elements such as straight lines (even several) can be visualised in most BIM viewers. Along the sections, the relevant geological information can be read out visually in the 3D models. The generation of sections along a curved axis is not possible with most solutions. Towards the end of the project, however, a new product came onto the Swiss market with which longitudinal sections along a curved axis (3D Polyline) are possible. In addition, it is also possible to apply the sections to several domain-specific models in a coordination model.

Visualising geological information in digital building models could be implemented and tested with the case studies. The requirements for the geological data were mainly limited to visualisation. The process for further analysis was not required in any of the studied application examples and this could thus not be tested. However, the capacity of comprehensive analyses offers great added value, which can also be applied in the future with the available results. Projects such as a remediation of contaminated sites, involving a direct quantification of the contaminating material, were addressed in the project, but not tested.

7.2.8 Dealing with uncertainties in the digital building model

The problem of uncertainty was discussed at length in the core team and with the advisory group. Different approaches were discussed and first implementations were carried out. The difficulty lies in quantifying the uncertainty and making it available. The responsibility lies with the geologists to prepare the information for the GEOL_BIM interface. In digital building models, the uncertainty is spatially visualised in 3D models. The description of uncertainty is described today, mostly in one dimension or also in the second dimension, in the form of additional lines in plans with additional symbols such as the question mark.

First synthetic examples have shown that the visualisation of uncertainty in digital building models generates a lot of added value. However, there are some limitations in the representation of uncertainty. In the case of a 3D surface consisting of a triangular mesh, it is not possible to assign additional attributes to the vertices of the triangles. A workaround was developed to circumvent this limitation. The vertices must be created as additional geometric elements, of the point or spherical geometry type, in order to then add the corresponding attributes of the uncertainty. In the digital building model, one can then evaluate both elements with each other and graphically represent the uncertainty at the vertices with colour gradients.
However, creating the vertices as additional geometric elements has the disadvantage that the files of the digital building models become larger, making editing or visualisation in the BIM viewers more difficult.
Furthermore, the approach of a derived uncertainty geometry from attribute values was tested. Unfortunately, this type of uncertainty representation is not supported by any of the current BIM viewers.

The investigations have shown that the potential for representing uncertainty in digital structural models is very large. Should it become possible to communicate the knowledge and uncertainty about the subsurface, in an open and transparent way, then this would help to decide whether the inferred risk is considered acceptable or not. Visualisations in coordination models could, for example, show that the risks to be borne can be minimised with only a few additional exploratory boreholes. This could open up new business areas for geologists and allow for a more resource-efficient and better dimensioned constructive solution.

8 Outlook

Much has been achieved in the GEOL_BIM Innovation Project (see Section 7). But there are also open questions that invite active participation. The harmonisation of geological information is an opportunity, if at the same time it is possible to maintain the necessary freedom to support geological workflows. The data models developed as part of the project will become the responsibility of the Swiss Geological Survey of the Federal Office of Topography swisstopo after project completion, where they will be maintained and, if necessary, further developed together with interested experts. For the future, the GEOL_BIM project team would like to see a continued open culture of exchange around collaboration in construction projects and for a jointly developed common language of applied geology – for a "with each other" in the construction process worthy of the name. An active community of geologists, civil engineers, builders, and others involved in construction projects would be considered highly desirable for this purpose.

To harmonise the exchange of information between clients and suppliers, the entire construction process must be sufficiently understood. Since in GEOL_BIM the information supply by the supplier was studied more intensively, the perspective of the client should also be integrated more strongly in the future. In future, it would be particularly helpful to be able to follow the flow of information in one or more construction projects across the design, planning and realisation phases.

Extensibility is an important feature of GeoSciML and the GEOL_BIM data model. Although it can be assumed that the methodology is transferable to further applications, it remains unclear whether the geology can be mapped holistically. It may be necessary to adopt existing extensions for GeoSciML in order to map hydrogeology with GroundwaterML in the future, for example. The common language as well as its implementation in the form of concrete subject-specific models will also require the commitment of subject experts in the future.

Within the framework of the project, the data models primarily highlighted the aspects of geotechnical engineering in the selected use cases. For broad use in the entire field of geology, other subject areas must also be considered accordingly and specific extensions to the reference and transfer model must be made if necessary. As a first priority, an extension to the subject area of hydrogeology is recommended, since this is relevant in many applications and with GroundwaterML there is already an established concept on which to build.

Irrespective of any subject-area extensions, the results now available require continuous maintenance. This includes, on the one hand, the ongoing updating and expansion of the standard attributes and, on the other hand, the value lists and classification systems of the data model. After completion of the project, the technical coordination and provision of these lists will be the responsibility of the Swiss Geological Survey of the Federal Office of Topography swisstopo, where they will be maintained and, if necessary, further developed together with interested experts

At the same time as the GEOL_BIM project, there are other ongoing projects abroad that are dedicated to the integration of geology into the BIM method. All these projects can lead to the further development of both geological foundations (e.g. GeoSciML) and IFC in areas relevant to GEOL_BIM. Following these developments and periodically reviewing the potential influences on the data model and the tools of GEOL_BIM is necessary so that any necessary adjustments can be planned and realised in good time.

In the medium term, an extension of the transfer model should be envisaged so that increased demands on the geological information can also be met and, for example, more relationships between the technical objects can be mapped. To this end, both content and technological clarifications are necessary in order to be able to introduce an alternative transfer format.

In geology software, semantic factual information is often added/attached to individual components of a geometry (e.g. on the vertices of a mesh). This allows information with a high spatial resolution to be managed and evaluated relatively efficiently in terms of storage. This approach deviates from the typical object-oriented approach and is therefore not supported by IFC. Possible approaches to transform such geometry-oriented factual information to IFC were discussed and should be deepened in further investigations. Possible solutions are seen in the use of voxel-like constructs, the extension of geometry definitions in IFC or the use of the geometry type for point clouds.

Important and widespread geological results use the principle of linear referencing (e.g. borehole logs, tunnel profiles). With the introduction of version 4.3 in IFC and the associated strong expansion to the area of infrastructure buildings, the principle of linear referencing will also gain strongly in importance in IFC and will be increasingly supported by BIM software. In a next development step of GEOL_BIM, the linear referenced objects are therefore to be systematically mapped with the structures provided by IFC for this purpose. Thus, this information could be evaluated linearly with standard functions of BIM software that will be available in the future, resulting in many interesting use scenarios, e.g. in the context of the standard of SIA199.

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