Artificial intelligence support for tunnel design in urban areas

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ABSTRACT: The article describes a comprehensive integrated project delivery approach based on digital transformation of the classic BIM (Building Information Model/Modelling) workflow and integration of project stakeholders by means of a single cloud-based IT platform. The topic falls into BIM technology and associated processes to support design, construction and operation of underground traffic connections based on maximal utilization of underground space in urban areas. The step forward is made by putting Information in central place of BIM. By the approach the requirements are fulfilled for state-of-the-art analytic methodologies - artificial intelligence utilization in civil engineering as we see in other engineering branches. The most important are state of the art optimization and decision support services; Better communication between the client, experts and public; Interdisciplinary collaboration between disciplines by multi-criterial decision support process.

1 INTRODUCTION

The results of research in the fields of AI (Artificial Intelligence) and cloud-based ICT (Information Communication Technology) solutions are becoming part of our everyday life through a rapid growth of available applications, services and products based on those technologies. Those enabling technologies triggered the digital transformation of many human activities to the point that traditional business models have been disrupted by the new digital economy. However, the adoption of these approaches within the construction practice for tunnel design and infrastructure design in general is still relatively slow and limited.

In recent years, big steps were made in the infrastructure design using the market available BIM software, which enables greater parametric control of the infrastructure and structural elements data. However, the following drawbacks of the current state of BIM are very clear:

- The purpose of BIM in its current state is not oriented towards the analysis of infrastructure effects and consequences of different design solutions. An important step forward was achieved by enhanced control of the input data, which further enabled parametric variation of design variables and control over them;
- Its inability to share data between models implemented with software tools offered by different suppliers (software companies);
- The traditional, linear design workflow is divided into numerous distinct steps from formalizing the client's idea to defining the architecture, geotechnics, structural design, etc., until forming of the final solution is confirmed. This approach is limited due to its linear workflow performed as a sequence of distinct steps (Figure 1), which seriously hinders the possibilities for controlled consideration of many interconnected infrastructure characteristics and effects.

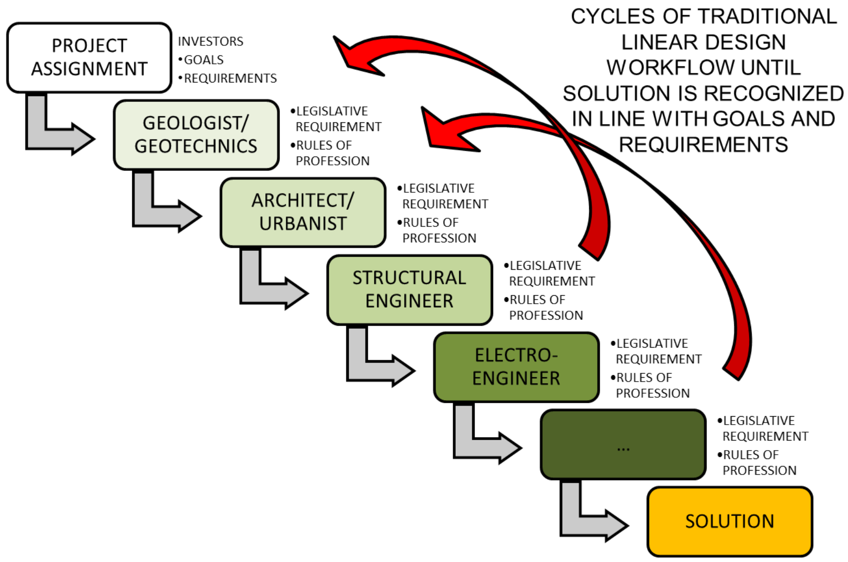


Figure 1: Traditional design process workflow

The consequences of these drawbacks include the possible loss of some important information within the workflow and the inability to efficiently control the workflow itself. In addition, the overall solution optimization and decision-making tends to be very limited, expensive and highly sensitive to human errors and obstacles due to the hierarchical nature of the workflow. This is even more problematic in the cases with complex mutually connected interdisciplinary problems that include clashes with existing infrastructure and assets in urban areas where cost/benefit and overall performance of the transport solution is very hard to achieve. To better address this challenging task, the traditional design approach was transformed into a data interconnected model, called the Information Model (IM), and a newly developed, cloud-based workflow. The IM workflow offers an important opportunity for tunnel design since it enables a clearly defined mapping from infrastructure variables (infrastructure information, element data, etc.) into infrastructure effects and consequences (see Section 2), which in turn are vital for a thorough and transparent examination and analysis needed for decision making. This was done for all stakeholders in design process to fulfill interoperability requirements in urban areas.
By described, we are opening opportunities for supporting the design process with the state-of-the-art AI technologies and ICT tools that integrates technologies for multi-objective optimization and decision support, and implements them with efficient cloud-based technologies. The process is tailored towards the optimal and transparent design of tunnels in the most challenging urban and other complex environments experienced in our construction practice and anticipated in the future. The process described in the article is particularly tailored to the tunnel alignment design, but the IM workflow platform is quite general and is applicable also to many other areas of infrastructure design:

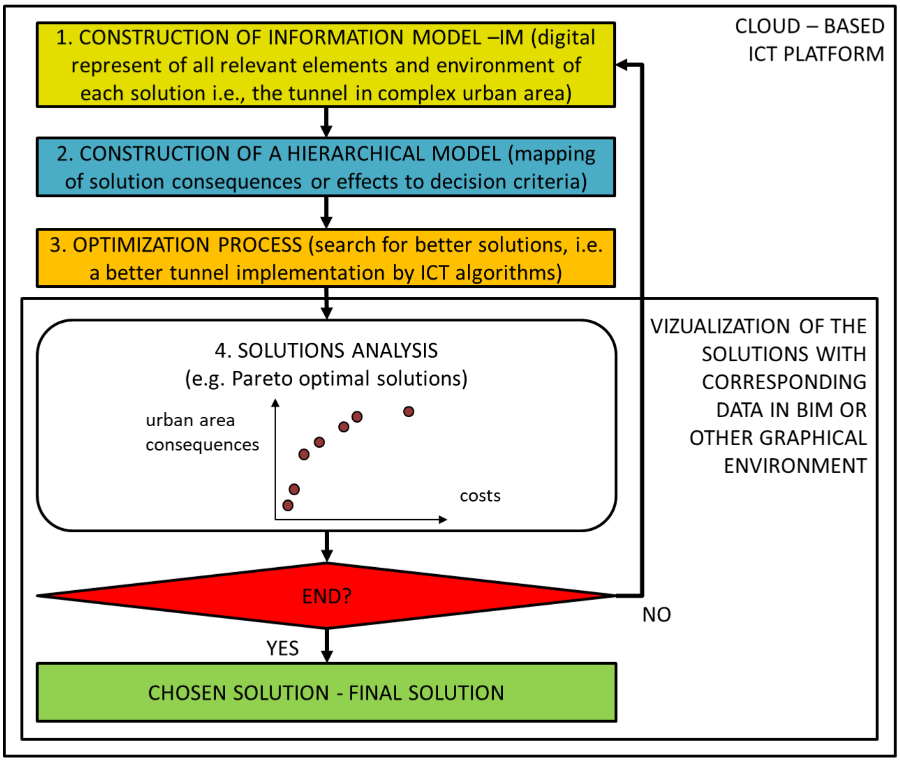


Figure 2: Steps of the proposed infrastructure design process

Above described workflow is designed for:

- Detailed and transparent analysis of tunnel alignment in complex urban areas;
- Interactive, interdisciplinary cooperation between the client, experts and non-experts, which is vital for building infrastructure in urban areas;
- Public participation and interactive cooperation of non-experts through a collaborative web-based platform;
- The solution offered as SaaS (Software as a Service). SaaS is a software licensing and delivery model in which software is licensed on a subscription basis and is centrally hosted (https://en.wikipedia.org/wiki/Software_as_a_service).

2 INFORMATION MODEL

2.1 *Description*

To fulfill the requirements of AI to support tunnel design, an enhanced information model as well as Level 2 BIM technology and associated processes is required. To achieve this, we need to consider the following tunnel design features:

- The nature of the tunnel design workflow. Each expert or non-expert participant (designer) needs to be included in the model concerning its responsibility and autonomy. This is done by partial models that communicate with other partial models via shared data space (input and output variables).
- Model requirements. The IM merges the project assignment and the partial models data of designers and stakeholders. This means that the data exchange is needed between traditionally used drawings, tables, numeric values, BIM, etc. This is achieved by standardizing input and output variables and storing them in a centralized, cloud-based, data repository.
- Data management requirements. The partial models and the project assignment need to be digitized in the form capable of representation of solutions by variables. Numerous solutions are expected to be explored by the optimization algorithms; therefore, digitalization is required regardless of the level of expertise of the designers involved.

To fulfill those, the IM is only one step in the workflow to acheive one-to-one mapping from the decision space to the effects/consequences of each generated solution (see

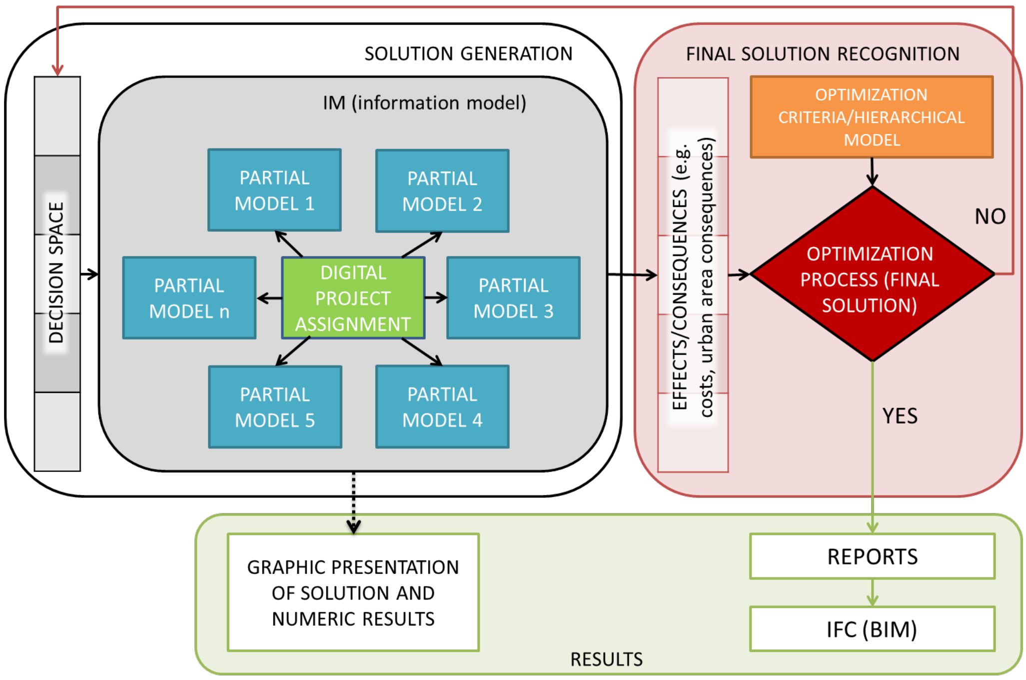


Figure 3).

Figure 3: The IM in the workflow

Each solution in the IM is constituted by many variables:

- Decision space (or search space) variables. Only few variables are relevant for optimization, e.g. the tunnel alignment axis, the tunnel cross-section, etc. During optimization, the decision space is explored to find the best solutions according to the given criteria.
- Other variables are defined by the digital project assignment (client) and partial models (by expert or non-expert designers).

To achieve the proper functionality of the IM reflecting the problem, proper data flows need to be established. This can be described by the following example: Figure 4 shows an example of the data flow between the partial models and the digital project assignment in the IM. Each designer (expert or non-expert) operates with its own specific data (e.g. rules of profession, legislative boundaries, etc.), which are represented by the corresponding partial model. The new approach of data sharing between partial models works as follows:

- The project assignment is the same for all participants in the IM, therefore it is digitized and shared with all partial models (designers and stakeholders);
- The decision space (DS in Figure 4) must be the same for all partial models for the generation of each solution;
- Different participants need different information or must provide it to specific partial models;
- Generated solutions are/needs to be admissible. Since partial models include specific legislative or profession-based requirements and limitations, the final solution of the IM includes all these features, which leads to admissible solutions for the optimization process;
- The approach enables equal involvement of non-expert stakeholders for which effects or consequences can be evaluated;
- Each partial model outputs its own effects/consequences (E/C in Figure 4) that are then gathered by the hierarchical model and used in the optimization process.

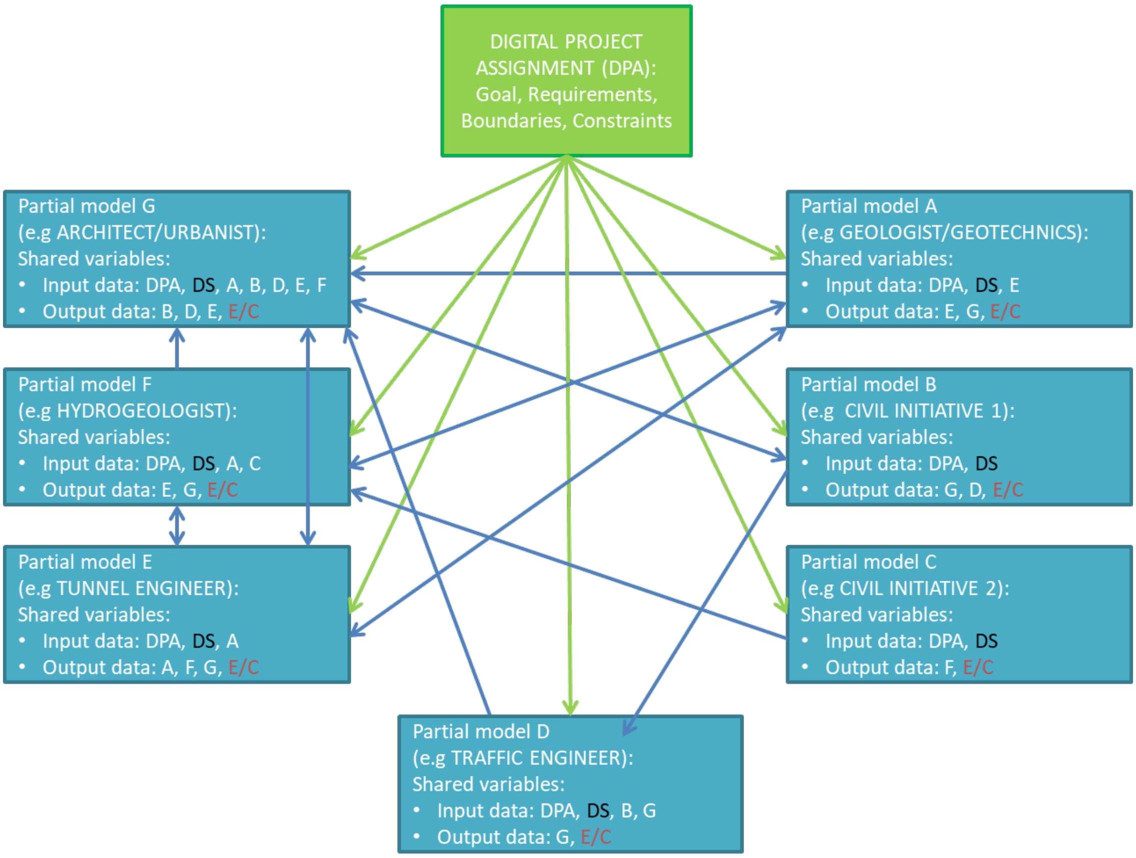


Figure 4: Shared variables between partial models of the IM data flow (an example)

2.2 *Relation to BIM*

By the solution in the form of proposed IM we are making a step from the effort focused on upgrades of traditional Level 2 BIM practices into open BIM or Level 3 BIM (as defined in Sacks et. all, 2018). This is done by data-based approach – approach where the information occupies the central role of the BIM process. Drawbacks of Level 2 BIM described in chapter 1 are alleviated by collaboration between relevant disciplines through IM which connects separate parametric models or parametric objects. This means that traditional BIM tools remains as constituting parts of the central information model (IM) e.g. Revit, ARCHICAD, Grasshopper for Rhinoceros etc. This way a new workflow and processes can offer following benefits:
- Full collaboration between disciplines on a single model;
- All stakeholders can access and modify that model in accordance with authorization rules;
- Model variables are stored in a centralized, cloud-based, data repository;
- Risk of conflicting data is minimized.

2.3 *Test model*

The IM approach was tested for the case of road tunnel alignment optimization with the focus on mapping from the decision space to the effects/consequences for each generated solution, which is a prerequisite for being able to use the optimization algorithm. A simple example of determining the optimal alignment solution is shown in Figure 5.
For this purpose, we have constructed an interdisciplinary parametric model in Dynamo plug-in for Revit (http://dynamobim.org/). Test model supports automatic generation of the necessary infrastructure elements (tunnels, excavations, embankments, bridges, etc.) on generated route axis. Route axis is defined by control points which defines decision space of the analysis:

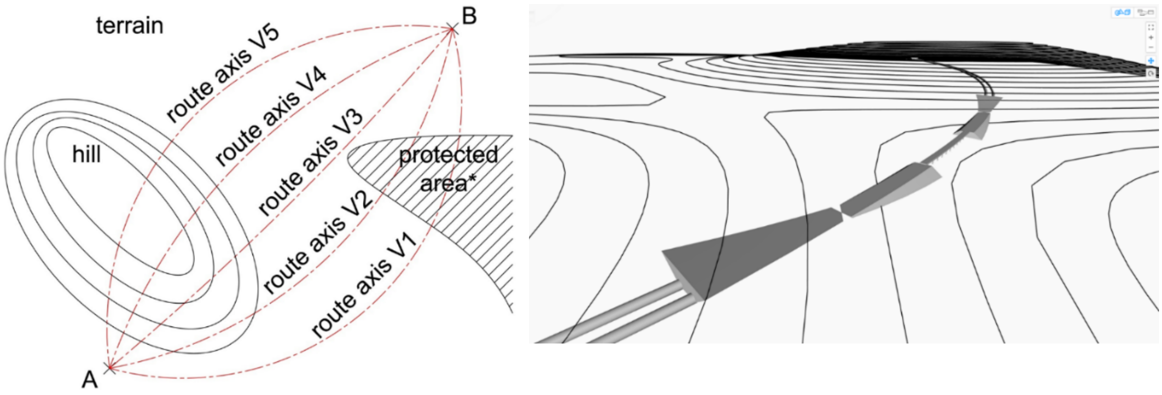
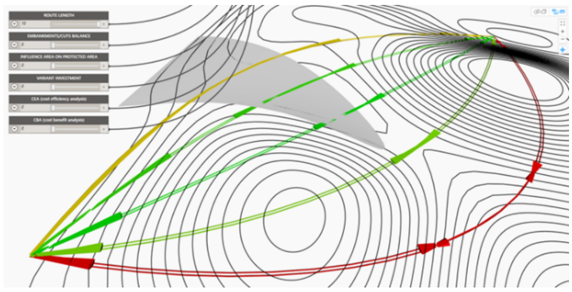
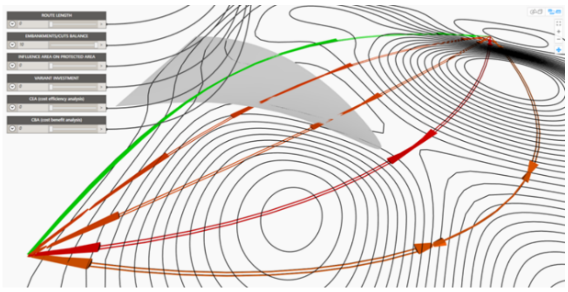


Figure 5: IM implementation example for automatic generation of the infrastructure elements using the parametric model

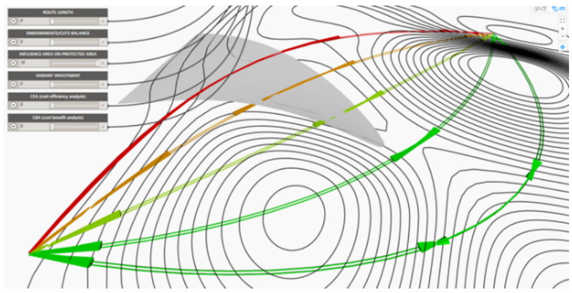
With such a model, the calculation of the corresponding effects/consequences for each solution can be done automatically. Figure 6 shows the four results obtained when one or more effects/consequences were selected as the sole criterion for the optimization:



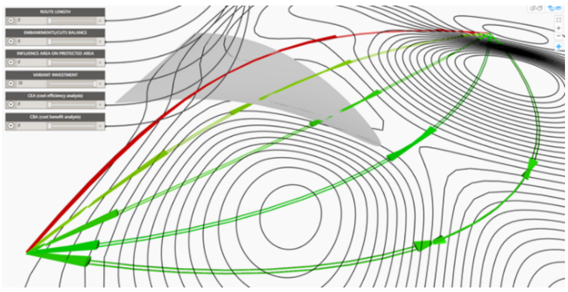
Results on the basis of the criterion:
ROUTE LENGTH



Results on the basis of the criterion:
EMBANKMENTS/CUTS BALANCE



Results on the basis of the criterion:
INFLUENCE TO PROTECTED AREA (gray area on upper left side of view)



Results on the basis of the criterion:
CONSTRUCTION COSTS

Figure 6: Results of the optimization of the test model for different optimization criteria (criteria 1 - 4)

This test has shown that the model is adequate for the proposed optimization purposes:

– Decision space variables or infrastructure attributes are values which can be connected to digital project assignment or shared by other models;
– Effects/consequences values for each solution are obtained automatically as predefined decision criteria.

The example visualized on figures shows only the result of optimization on the basis of one criterion – one criterion for each subfigure. In case of multiple criteria the optimal solutions are not so obvious. This is even more important when the criteria are mutually exclusive. The approach for such cases is explained in Sections 3.3 and 3.4.

3 AI TECHNOLOGIES

3.1 *Artificial intelligence*

Artificial intelligence (AI) is a science and research field investigating methods and technologies that enable machines (computers) to perform tasks that typically require human intelligence (a quite loose definition, a more detailed discussion on different definitions can be seen, e.g. in (*Russell & Norvig, 2014*)). Although the development of AI started already after the Second World War, within the last decade we are witnessing the appearance of many AI-based applications and services offering support, as well as previously unimaginable solutions in different areas of human endeavor, including science, engineering and everyday life. Currently, the most prominent area of AI is machine learning, which is typically used for data-driven modeling of complex systems and gave rise to notorious applications such as chess, and go playing. Other AI disciplines include decision support systems and evolutionary computation, and it is the technologies from these two disciplines that we use in the proposed optimization workflow:

3.1.1 *Decision Support Systems*

Are information systems for the support of the approach in the form of:

- Knowledge Representation is an important aspect of decision models, which serve also as a formalization of domain knowledge about various decision factors and their relations. By applying algorithmic reasoning and analysis capabilities on structured and formalized human-provided domain knowledge, we are combining the best capacities of humans and computers. Decision models therefore serve as knowledge representations and mechanisms for transparent and elaborate reasoning and simulations. This relates well with decision making in tunnel design in urban areas, which is influenced by many goals, opinions and interests, which are hard to grasp for a human to reason about, but also impossible for a computer to efficiently learn from empirical data. Even by using the models for knowledge representation only, one can recognize a limited set of good options from a large number of acceptable ones that are gained from optimization algorithms.
- Multi-Criteria Decision Modelling (MCDM) is aimed at formal (mathematical) modelling of decision problems that consider a multitude of criteria. A model of this kind represents a formalization of the specified problem and usually enables assessment, visualization and comparison of decision alternatives. There are several established and mature decision modelling methodologies like *MAUT (Keeney and Raiffa, 1993), AHP (Saaty 2008), Electre (Figueira, 2005) and DEX (Bohanec et al., 2013)*. The last one is especially well suited for problems that are hard to quantify and influenced by many goals, opinions and interests, such as the problems related to Smart cities.

3.1.2 *Multi-Objective Optimization by Evolutionary Algorithms.*

Evolutionary algorithms are iterative methods that improve on solutions using principles that mimic the natural evolution such as selection, crossover and mutation (*Eiben & Smith, 2003*). Because they operate on populations of solutions, they are especially appropriate to handle multi-objective optimization problems, where, due to conflicting criteria, multiple optimal solutions exist—each representing a different trade-off among the criteria (*Deb, 2001*).

The use of AI technologies in optimization and decision support helps automate and speed up the tunnel design process, while the final decision is still made by humans (the decision-making team). Additional benefits of using AI technologies in the proposed process are:

- Effective exploration of the decision space that enables us to find a large number of admissible solutions, some of which could not be conceived by the designers.
- The objectiveness (given the provided inputs and rules) and increased transparency of the decision-making process reduces the risk of subjective judgements of stakeholders, omission of important consequences, lack of design goals and violation of valid constraints.

On the other hand, using AI technologies in such an application has its limitations:

- If the decision space is large and the partial models very complex, there might not be enough time for the optimization algorithms to find all the optimal solutions. In such cases, the final decision has to be made on near-optimal solutions.

– Although AI techniques speed up and automate the design procedure, they are only as good as their input. If the problem is not defined well, the returned solutions might not be appropriate or even admissible.

3.2 *Construction of a hierarchical model*

The construction of a decision model is a collaborative process in which domain experts provide necessary domain knowledge, such as relevant variables, target concepts and the rules and constraints that need to be considered. After this is done, a decision analyst takes care of proper and effective formalization. In our proposal, the hierarchical MCDM methodology is used to define the aggregation transformations of raw data inputs (measurements) into higher level concepts (criteria), which are afterwards used in the optimization process (see Figure 7 at the bottom left).

3.3 *Multi-objective optimization*

Figure 7 shows how multi-objective optimization is used to find optimal solutions in the tunnel alignment problem. The two considered criteria are the costs (to be minimized) and the benefits to the urban area (to be maximized). These two criteria are conflicting, i.e. achieving favorable urban area consequences usually comes at a high cost, while low-cost solutions can bring unwanted consequences to the urban area. To solve such a problem, multi-objective optimization algorithms search among all admissible solutions from the decision space so that both criteria are optimized. The optimization process ends when enough (optimal) solutions have been found. The result is a set of solutions.

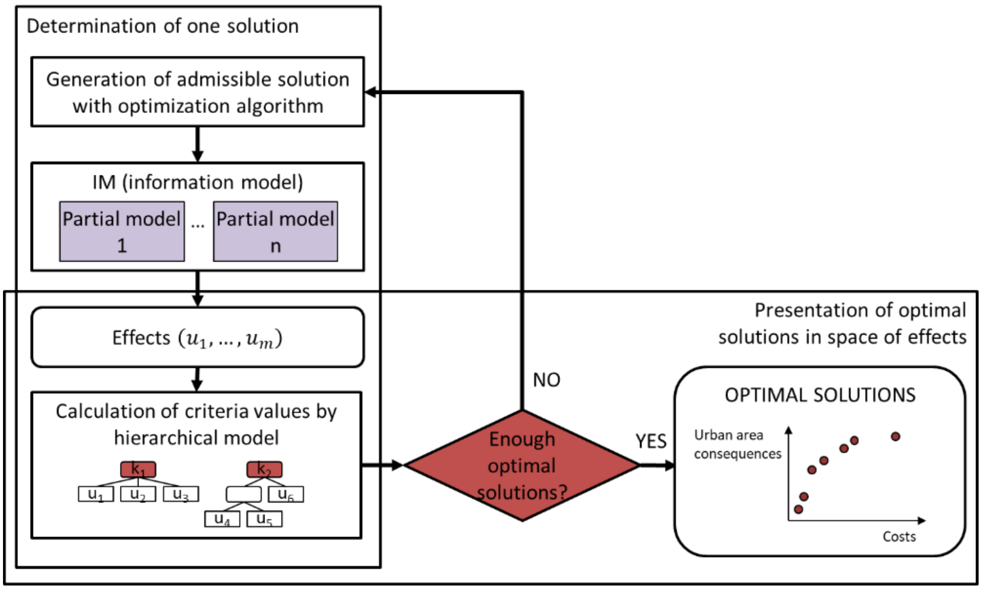


Figure 7: Multi-objective optimization in the proposed process

The recognition of many optimal solutions is the most important improvement over the traditional design practice since all these solutions are non-dominated – they all lie on the Pareto front (the graph on the right side of Figure 7). This means that no solution dominates any other and none of them can be improved in one criterion without degrading the value of the other criterion. The final solution is chosen after the solution analysis step (Section 3.4).

3.4 *Solution analysis*

The criteria used in optimization already have their hierarchical structure defined, as well as the rules of how the criteria are calculated from input values. This allows for a subsequent (posthoc) analysis of the solutions proposed by the optimization methods, as (particularly *DEX*) MCDM allows for easy and transparent comparison of alternatives, analyses of trade-offs among them and sensitivity analysis.

4 A CLOUD-BASED TUNNEL DESIGN SOLUTION

BIM and other infrastructure design tools provide a practical platform to manipulate data and visualize building elements. The IM involves this toolset as described in previous sections. In addition to these technical needs, with the development of cloud-based solutions we are further digitally revolutionizing the tunnel and infrastructure design industry, introducing new business models and gaining a competitive advantage over other actors. The implementation of the cloud-based IM workflow is built upon our expertise in the introduction of cloud-computing, big data, cybersecurity and analytics solutions across a range of industries, from healthcare to IoT (Internet of Things) applications.

From the stakeholders' point of view, a properly implemented proposed workflow as Cloud Computing solution provides several advantages over classical approaches. It allows actors in the design process to focus on their core business instead of spending resources on the maintenance of own ICT infrastructure. Consequently, ICT costs decrease significantly, as the upfront investment is minimal. The used cloud infrastructure is charged on demand (pay-as-you-go), meaning that during tunnel design optimization/simulation phases there is a surge in use of computational resources, while most of the time those resources are not needed, thus not charged to the end user. Maintaining own servers for this purpose means that effectively, the infrastructure is oversized to support sporadic needs for lots of computational power.

Collaboration, data sharing, secure access and multitenancy are all concepts that are introduced by design from the very beginning of the development process. The cloud-native workflow has been designed and implemented to support those needs. This approach allows effective introduction of the SaaS (Software as a Service) business model in tunnel design. The workflow is licensed on subscription basis to clients/stakeholders, while the system is cloud-hosted. This model allows efficient ICT management and support, allowing clients to obtain access to the system from the moment they need it. There is no need to purchase and deploy additional ICT equipment. The data is stored securely, which includes strictly controlled access rights as well as guarantees of continuous backups and data-accessibility.

5 CONCLUSION

The wave of digitalization (known as BIM-Building information models/modelling) introduced a new design technology, processes and also vision to the architecture, engineering and construction industry. The most important are digital parametric representation of the objects and efficient data management to describe the characteristics, state or behavior of the object through concerned time period. Despite these achievements we see that state-of-the-art analytic methodologies and ICT within civil engineering is not on the level we see in other engineering branches.

Based on years of practical experience and knowledge acquired through cooperation with high-tech ICT companies and scientific research institutes, we decided to combine our knowledge and experiences to:

- Enhance traditional design approach based on BIM by putting information (data) in central place of modeling process. Proposed Information Model (IM) enables coherent consideration of non-expert disciplines in tunnel design, construction and operation e.g.: civil initiatives, public participation and other relevant societal groups;
- Develop a practical approach for utilization of state-of-the-art ICT to offer new solutions to tunnel design problems. The support is on the highest ICT level compared to other engineering disciplines.

The result is new workflow and procedures for decision making and optimization support for underground traffic connections based on maximal utilization of underground space in urban areas. This topic is becoming very important due to fast urbanization of society, migrations and other societal changes/challenges of the future.

6 ACKNOWLEDGMENTS

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