A Novel Knowledge-Based Engineering Approach for Infrastructure Design

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Abstract

In this paper, we present a novel Knowledge-based Engineering approach for the preliminary design of infrastructure constructions. To this end, a system architecture is presented which ensures the independence of knowledge representation and product modelling. For this reason, the knowledge base and rule engine are implemented in a KBE control centre, which runs separatly from the modelling and simulation modules. In particular, the integration of the KBE system within the BIM-based planning process is considered. Using open data formats like the Industry Foundation Classes (IFC), downstream applications could be accessed via standardized interfaces and thus easily used for simulation purposes. We present a Visual Programming Language (VPL) approach which implements La Rocca's High Level Primitives (HLP) and Capability Modules (CM) for the geometric-semantic modelling of the building product model. The use of a VPL carries certain advantages, such as improved dependency tracking and decision transparency for the user. As a VPL is used, we establish an Abstraction Layer Concept (ALC) for hierarchical structuring of HLPs and CMs. The suggested approach provides the basis for next generation infrastructure design and will significantly contribute to a more efficient, cost-saving and high quality planning of infrastructure projects in the future.

Keywords: Knowledge-based Engineering, Building Information Modelling, Virtual Design and Construction, Infrastructure Design, Decision Support

1. Introduction & Motivation

In the field of infrastructure construction different interests of owners, population, authorities and contractors as well as difficult technical constraints and the growing number of stakeholders lead to more and more complex design processes. At the same time, decisions made by civil engineers should ensure a balance of functionality, operability, maintainability, sustainability, aesthetics, time and costs of a structure. Today, engineers base the decision-making process mainly on their experiences and estimations.

Today, engineers use CAD systems for creating 2D drawings and – to some extent – 3D models of civil engineering structures such as tunnels and bridges [1]. However, the usage of these systems does not allow to incorporate the expertise and experience of the engineers and reuse it for similar issues. By the application of Knowledge-based engineering (KBE) methods for infrastructure planning repetitive processes can be automated, especially in early design phases of bridge and tunnel planning [2,3].

It is therefore desirable to capture the know-how of individual experts within a company, to store it centrally, to provide it to other engineers in a company and finally reuse this knowledge for similar design tasks. Since the 1980s, so-called Knowledge-based Systems (KBS) have been studied in a general approach [4], to digitally represent and reuse expert knowledge. KBS are software systems which solve complex tasks analogous to human experts by means of a knowledge base and inference (logical conclusions based on facts and logical calculus). The application of KBS in the field of Computer-Aided Design (CAD) is consequently called KBE. To support the design process of engineering products, engineering knowledge is represented by formal, computer interpretable rules. Since this rules are then taken into account in the course of the geometric-semantic product modelling process, one speaks therefore of knowledge integration [5].

Knowledge-based Engineering techniques have been intensively studied in other domains such as automotive [6–8], aerospace [9–11], or ship engineering [12–14]. Except for a few studies [15,16], KBE has not been widely adopted in the Architecture, Engineering and Construction (AEC) industry, dominated by Small and Medium-sized Enterprises (SMEs) [17], so far. In consequence, the civil engineering CAD systems available today do not provide KBE functionalities. However, the application of KBE for infrastructure design is promising, as these constructions hold a straightforward component structure. Furthermore a large amount of already formalized engineering knowledge in codes and regulations which govern the design of these facilities exists.

Right now a fundamental change in the AEC industry by the introduction of the Building Information Modelling (BIM) technology [18] takes places. BIM aims to represent the complete building facility in a digital product model [19], which is used throughout the whole life-cycle. In the context of BIM, tools for Rule Checking [20] and Code Compliance Checking [21] are well known. These systems intend to check a designed building information model against defined rules to ensure compliance with codes and regulations. KBE is based on a fundamentally different approach: Instead of applying rules on the completed product model, rules are used throughout the design of the product. This is also denoted as the “generative character” of KBE systems.

2. State of the art

2.1. Infrastructure design

Preliminary infrastructure design focuses on the exploration of various design options leading to an optimal or near-optimal design solution with regard to technical, ecological, creative and economic aspects of the planned structure. The generated design solution serves as a basis for determining the construction costs, preparing the tendering, elaborating the detailed design and finally executing the construction work itself. The design of infrastructure facilities is a highly iterative process, and heavily dependent on external conditions, such as the location and the intended function of the structure. As part of the bridge design, a bridge structure is described by the essential design elements like superstructure, substructure, foundation, abutment, support, bridge equipment, materials and construction methods. For each component a huge number of corresponding regulations and guidelines specifying the design and function exist. As well as for bridges, the same applies to the design of tunnels. Throughout the tunnel design in particular the native soil plays an essential role in the choice of the construction type.

The preliminary design is also basis for decision-making by the involved stakeholders. Today public construction projects are regularly characterized by budget overruns of up to twenty percent. In civil engineering, the construction costs are evaluated from the publicly communicated preliminary design. Here, the use of KBE can make a significant contribution towards a greater planning security. By applying rule-based design and knowledge integration to infrastructure design, detailed predictions about the cost and construction time can already be made in very early stages of the design.

2.2. Building information modelling for infrastructure

BIM offers significant advantages in many areas of planning and construction of infrastructure facilities. Working with a 3D model ensures that the derived views and sections are always consistent with one another. BIM improves the coordination of various disciplines and makes it possible to detect and fix collisions at early design stages. Quantities, which are determined from a digital building model, provide a reliable basis for the tender, award of contracts and accounting. Before beginning with the construction work, the 3D BIM model can be combined with the scheduling and thus, a 4D BIM model is created, which allows the verification of the construction processes and the planning of the construction site logistics. If a digital building model is handed over to the building owner after completion of the construction project, the owner can use it immediately for facility management. In contrast to building construction, where the spread of BIM is already well advanced, the current adaption level of BIM for infrastructure marks only the beginning of a promising development. In Figure 1 a BIM model of bridge is shown.

For the success of BIM, the lossless exchange of high-quality building product models using vendor-independent, open interfaces plays an important role. For this purpose, the Industry Foundation Classes (IFC) is an open data format for the exchange of product models within BIM [22]. The international standardization has already reached a very good level in the definition of neutral formats for the exchange of digital building product models.

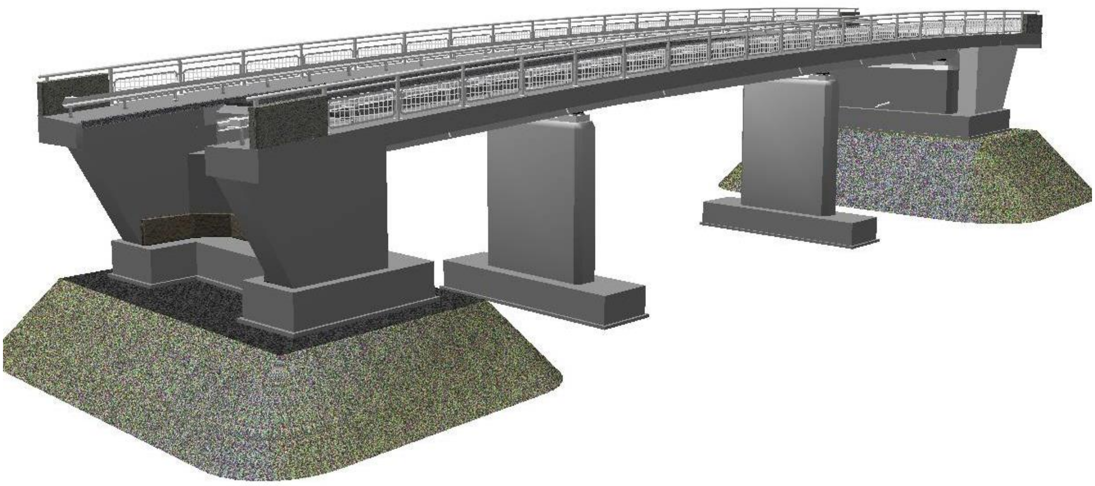

Figure 1: Building Information Model of a bridge [23]

Developed by buildingSMART the IFC standard has become an ISO standard in 2013 (ISO 16739). Unlike the exchange of product models of buildings, there is currently no possibility to exchange product models of infrastructure facilities via IFC. Nevertheless, IFC will also play a major role in infrastructure design for the exchange of building information models in future. Therefore, IFC as a neutral data format should be considered in the system architecture of our proposed KBE system for infrastructure design. The use of IFC carries several advantages, as there are: Accessibility of downstream applications via standard interfaces, independence from proprietary data formats and software systems (OpenBIM), customizability and extensibility by users and higher acceptance for usage of the proposed KBE system in SMEs.

3. Knowledge-based Engineering

There are several advantages by using a KBE system for infrastructure design compared to using traditional CAD systems. The biggest advantage is the reduced product development time by streamlining and automating repetitive, not creative design processes. Knowledge-based engineering can always be used beneficially when a "significant share of the design decisions can be clearly precipitated by the automatic evaluation of design rules" [24]. This is particularly true for product developments where,

- a high degree of similarity between product versions exist,
- a large number of customization options exist,
- a large number of design processes exist,
- many competing or conflicting requirements exist,
- knowledge from many different sources is available and has to be considered,
- the design is affected by many disciplines,
- many iterations are performed towards the final design,
- a high amount of resembling time-consuming but primitive design tasks exist,
- many decisions during the design process have to be made.

Moreover, KBE enables a fast and dynamic exploration of design alternatives within the (preliminary) planning process. The user may explore many "if-then" scenarios and gets a well-performing design solution in a much shorter time. This also creates opportunity for the creative solution of other technical problems. In Figure 2, a comparison of product development time between KBE and traditional CAD is depicted. Compared to the traditional CAD usage with approximately 80% repetitive tasks, this percentage can be significantly decreased by applying KBE. This reduces the overall product development time and allows the engineer to focus on the true technical challenges.

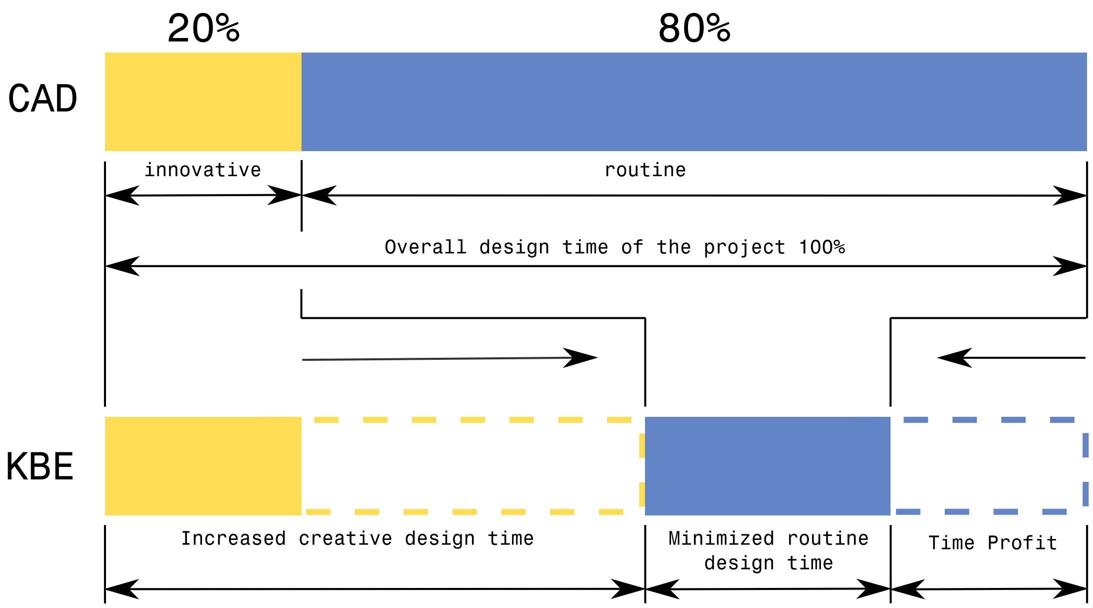

Figure 2: KBE compared to traditional CAD [25]

The application of KBE in infrastructure design holds, considering the large number of similar planning tasks, great potential. By reusing engineering knowledge repetitive planning processes of the bridge and tunnel planning can be (semi-) automated in order to gain time while simultaneously increasing planning quality and reduce costs. The circumstances of a large number of standards and regulations, the high amount of possible bridge or tunnel options and the use of many standardised components are predestined for the use of knowledge-based engineering methods in infrastructure design. In summary, the available knowledge is already highly formalized.

For example, the construction of a bridge abutment, is a regularly recurring planning process throughout the bridge design, where the requirements are always the same. The abutment geometry is standardized by codes and guidelines, the design variants are mainly affected by the native soil and terrain. Thus, the automation of this design process using a KBE system is easy and straightforward. The same applies analogously to other bridge components like superstructure, piers or foundation or other engineering structures such as tunnels, locks, hydroelectric power plants or dams.

4. Concept

Today, for all mayor, mechanical engineering related CAD systems corresponding KBE modules like Knowledge Fusion for Siemens NX or Autodesk Intent for Autodesk Inventor exist. These systems are often criticized for their close integration in commercial CAD systems [26]. In those systems, knowledge is formalized in a proprietary software systems and knowledge is therefore not available outside of those environments. At the same time, open source and independent KBE systems like Genworks [27] and their declarative programming languages are often complicated to learn and handle, even for experts with programming skills. In order to overcome these disadvantages and to take into account the specific AEC requirements, the key elements of our approach are the following:

- Separation of knowledge base, knowledge processing and product modelling, unlike current proprietary KBE systems
- Use of production rules and decision trees with inference features and graph-based rule editing
- Use of a VPL for geometric-semantic modelling of BIM models; introduction of Abstraction Layers
- Use of La Rocca's high-level primitives and capability modules and adaption of the Multi Model Generator for AEC purposes
- Performing a "Discipline Breakdown", meaning the rule-based sub-division of the BIM model into discipline models
- The use of the open data format IFC

4.1. KBE Control Centre

As part of his PhD thesis [28], La Rocca developed a KBE driven multi-model generator (MMG) for aircraft design. MMGs "are KBE applications able to automatically generate models of a specific family of products, e.g. […] complete aircraft configurations and, for each model, to create the discipline abstractions required by the various analysis tools, in the framework" [2]. This concept can be adapted very well to a KBE system for infrastructure construction considering the BIM planning process and the construction-specific requirements, resulting in the system architecture depicted in Figure 3.

At the beginning of the iterative design process, requirements are defined by the user. These are general constraints on an abstract level like the track alignment and the terrain or the type of bridge system. Based on these facts, the KBE control centre then takes over the management of the entire KBE system and its processes. The control centre contains the modules *knowledge base* and *rule engine*. Based on the defined requirements the rule engine sets more detailed parameters by applying predefined rules to the given facts. For example if the road class and the number of lanes leading over the bridge is given by the user, the parameter width of the superstructure is set by the rule engine. To manage the rules in a knowledge base a graph-based rule editor is available. In addition, functionalities for version control of the generated models are included in the control centre.

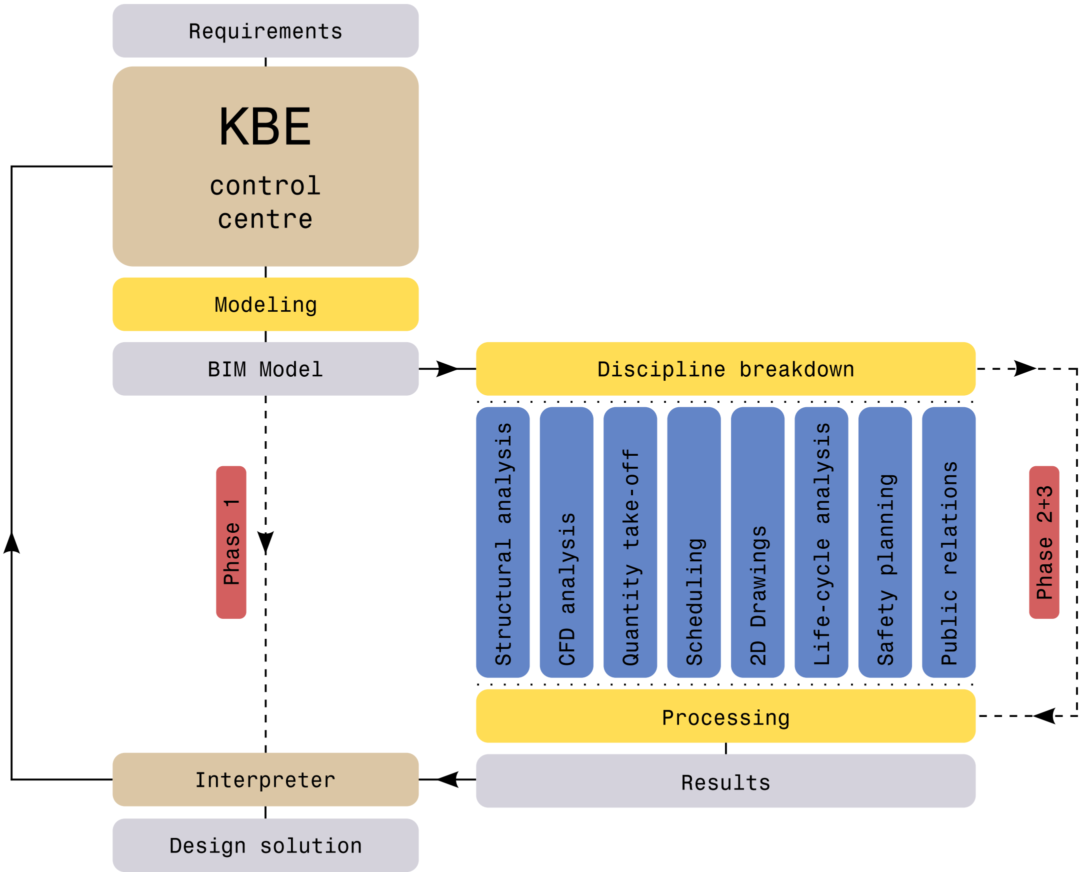

Figure 3: KBE system architecture

The geometric-semantic modelling of the BIM model is realized by a decoupled, freely selectable visual modelling system (Dynamo or other) which uses the pre-set parameters of the KBE control centre as input. This system architecture ensures the independence from a particular CAD system, but requires communication channels for the exchange of parameter values. The result of this modelling step is a BIM model in multiple levels of detail.

With the help of the Discipline Breakdown step, discipline models are abstracted from the previous generated BIM model. This step is necessary since abstractions of the detailed BIM model are required by various downstream analysis and simulation tools, like structural analysis, CFD simulation, Quantity take-off, Scheduling, 2D Drawings, Life-cycle analysis, safety-planning and public relations. For instance for structural analysis of bridge piers a pillar is abstracted to its axis and cross section, whereas a pillar slab is modelled as a surface with a certain thickness.

Whether a Discipline Breakdown step is performed or not is dependent on the application phase of the KBE system. We therefore introduce three KBE Development Phases:

Phase 1 - Interpretation of the BIM model based on rules of thumb: Fully automated and rule based adjustment of the model parameters driven by the rule engine in the KBE control centre. Based on integrated rules of thumb or simple formulas. No Discipline Breakdown is performed, since no derivations of discipline models and no simulations are executed. Thus, the iteration cycles can be kept very short.

Phase 2 - Manual Discipline Breakdown: Derivation of discipline models generated from the BIM model. Manual interpretation of simulation results and adjustment of the parameter values by the user. Due to long simulation runs, long iteration cycles appear.

Phase 3 - Automated Discipline Breakdown: Equal to Phase 2, but automated interpretation of simulation results. Suitable for long-term optimization of the design in non-interactive mode.

4.2. High Level Primitives and Capability Modules

To simplify the geometric modelling for non-experts so called High Level Primitives (HLP) and Capability Modules (CM) are adapted for the design of infrastructure. HLPs are abstract geometric-semantic objects, which all together represent the digital building model completely. One can also speak of the least common denominator of all bridges and tunnels. The concept was developed and used by La Rocca [2] as part of the Multi Model Generator (MMG). A similar approach is known from Amadori [29], the so-called High Level CAD templates.

Unlike geometrical primitives such as cube, sphere or cylinder the geometry and topology of HLPs can be modified by adjusting the input parameters based on the implemented rules. Similar object structures from commercial software systems, known as families (Autodesk Revit) or SmartParts (Nemetschek Allplan) miss the capability of a rule-based modification of geometry and topology. HLPs can be freely combined with each other and have clearly defined input and output interfaces. Moreover, it is possible to structure the HLPs hierarchically (sub-HLPs).

For example, throughout the modelling of bridges, essential components like superstructure, substructure, foundation, abutment, terrain, and alignment can be implemented as High Level Primitives. Via the defined interfaces, information is exchanged between the primitives. For example, reference planes are provided by the HLP “superstructure”, which in turn serve as a reference for other HLPs like the HLP “substructure”.

In Capability Modules (CM) actions are encapsulated, which analyse HLPs and use functions for other processes such as export / import functionalities. Thus, in CMs mainly procedural knowledge is stored. With regard to infrastructure design, they form the basic functionalities for the Discipline Breakdown. By clever instantiation of the HLPs and CMs an infinite number of bridge or tunnel variants is theoretically possible. Both the HLPs and CMs can be implemented as nodes in a VPL. The implementation of HLPs and CMS is therefore highly dependent on the VPL used.

4.3. Visual programming

Visual programming languages (VPL) have been developed since the 50s [30]. These programming languages are formal, graph-based languages, which are defined by graphic objects consisting of nodes and connections and by suitable arrangement thereof. VPLs are easily interpretable and learnable by humans which allows the use without extended programming skills. In the context of BIM, VPLs becoming increasingly important for steering the geometric modelling process. Thus, for all major BIM tools visual scripting components exist: for Autodesk Revit it is Dynamo [31], for Rhinoceros it is Grasshoper [32] and for the Bentley platform there is Generative Components [33]. For Vectorworks, Marionette is in development. With the help of nodes and tubes an architect or civil engineer defines the modelling steps. The geometry may be modified accordingly by adjustment of the input parameter values.

So far, the geometric modelling process in the context of KBE systems is performed with the help of hardly understandable declarative languages or directly in the attached CAD systems. These languages are difficult to understand for users or experts without programming skills. Due to these shortcomings, we introduce the usage of a VPL in the presented approach for geometric modelling. Furthermore, the VPL can be used as an explanation facility, decision transparency and for dependency tracking. Figure 4 shows the implementation of the HLPs superstructure and substructure in a VPL.

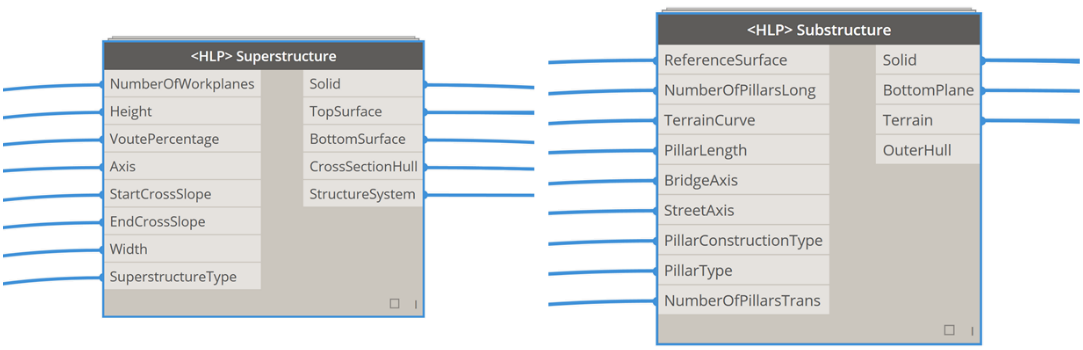

Figure 4: Implementation of the HLPs Superstructure and Substructure in a VPL environment

4.4. Abstraction Layer Concept (ALC)

The implementation of HLPs and CMs in a VPL allows a hierarchical structuring of these elements. Therefore, so called Abstraction Layers (AL) are introduced, see in Figure 5. Starting at the top most AL the structure leads to deeper and deeper layers, where rules or geometrical objects are implemented in more detail. The basis for the use of ALs is formed by the use of HLPs and CMs. By introducing ALs, it is possible to implement security mechanisms and a role management system. Thus users are allowed to access certain layers depending on their level of expertise. If necessary, these access rights can be reassigned within the company for every new project.

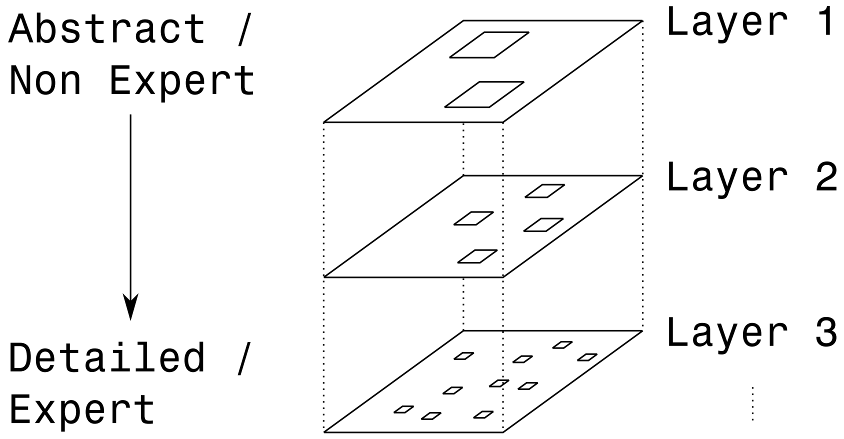

Figure 5: Visualisation of the Abstract Layer Concept

5. Proof of concept

As a first proof of concept of the presented approach, we implemented the geometric-semantic modelling part in the VPL environment Dynamo, see in Figure 6. This implementation will serve as a basis for integrating the KBE control centre in the future. Right now we are able to generate a bridge model driven by a parametrized bridge axis and the terrain for testing purposes.

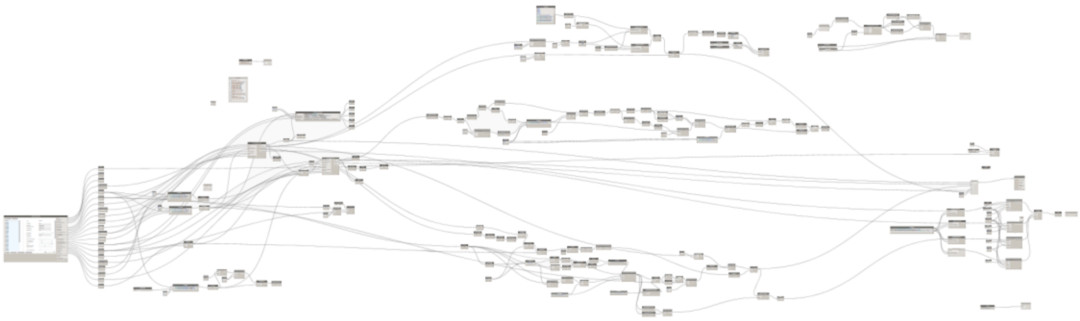

Figure 6: Graph network for bridge modelling in the VPL environment Dynamo

The modelling process begins with defining the input requirements in a so called “version control node”. These are abstract parameters like bridge type, superstructure type, pillar type, number of piers in longitudinal and transversal direction and many more. Then the modelling of the bridge axis and terrain follows. The superstructure solid is modelled by the *HLP superstructure*, using additional parameters like start and end cross sectional slope, superstructure type, height and width. We implemented interfaces for each HLP, which supply other HLPs with reference objects, since all HLPs have to interact with each other dynamically on runtime. This is why the *HLP superstructure* also provides, beside the superstructure solid, reference surfaces and an outer hull geometry object which can be used by other HLPs to perform their construction steps. For example, the *HLP railing* requires the top reference surface for modelling the railing of the bridge. The *HLP substructure* the bottom reference surface and the terrain reference surface for modelling the substructure. When all modelling steps are executed, the complete BIM model of the bridge is built up, see in Figure 7 and 8. All described high level parameters are fully independent and freely combinable.

Figure 7: Bridge BIM model generated by the KBE prototype, version 1

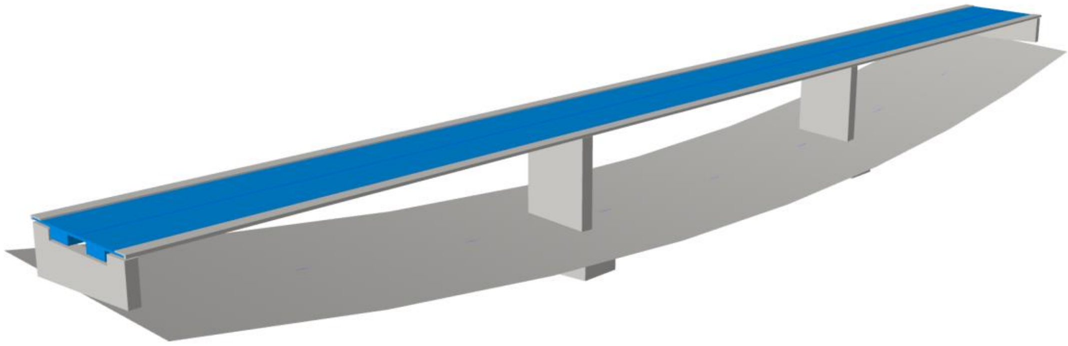

Figure 8: Bridge BIM model generated by the KBE prototype, version 2

Apart from the HLPs, we implemented a *CM structural export* is implemented which extracts disciplines models from the BIM model. These disciplines models later then serve as an input for several analysis tools. Currently, the prototype implementation still has some restrictions: only girder bridge support; no modelling of reinforcement; no detailed bridge components like railing, drainage or deep foundation available; CMs for the import of alignment or terrain data; and for the export of more discipline models missing. Additionally, the interpretation of the simulation results has to be performed manually.

6. Conclusions

In this paper we presented a novel KBE approach for infrastructure design and the concept on which our approach is based on. Since KBE represents the engineering knowledge in formal computer-interpretable rules, then they can be processed by computers. The application of KBE in infrastructure design enables the automation of repetitive design processes and thus saving time. The major challenge is the way of formalizing knowledge in order to achieve a high degree of transparency and customizability for the user and a system architecture which ensures independence from proprietary CAD systems. In our approach we therefore introduced a number of techniques like VPLs and the ALC and integrated them into existing concepts like La Rocca's HLPs, CMs and MMG, which were adapted for the application in infrastructure design. The combination of these technologies and concepts results in the presented KBE system architecture. The introduced concept and KBE system are still a work in progress and further improvements are under development. Nevertheless we showed the great potential of applying KBE methods to infrastructure design. We will investigate other areas of application in AEC, for example, for the design of highly regulated buildings like industrial halls, railway stations and platforms, cableways, offshore installations, water supply, waste disposal systems or pipeline routes.

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