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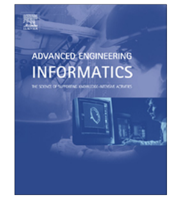

Full length article

Using graph rewriting methods for the semi-automatic generation of parametric infrastructure models

Simon Vilgertshofer *, André Borrmann

Chair of Computational Modeling and Simulation, Leonhard Obermeyer Center, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany

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ABSTRACT

For the design of large infrastructure projects such as inner-city subway tracks, it proves necessary to consider differing model scales, ranging from the scale of several kilometers down to a few millimeters. This challenge can be addressed by using multi-scale product models comprising multiple levels of detail (LoD). Ensuring consistency across the different LoDs can be achieved by applying procedural and parametric modeling techniques while creating the model. This results in a flexible multi-scale model that can be easily modified on one scale while other scales are automatically updated. However, the correct application of parametric constraints and procedural dependencies has shown to be a very complex and time-consuming process. To address this issue, this papers presents a semi-automated detailing mechanism, which is based on formal procedures based on graphs and graph transformations. This paper discusses how procedural parametric models based on two-dimensional sketches can be represented by graphs and how detailing steps in the form of parametric modeling operations can be formalized by using rule-based graph rewriting.

1. Introduction

The ongoing digitization of planning processes in the building sector has become a major improvement for the AEC industry and is being expanded into the infrastructure domain [10]. In the planning of large infrastructure facilities ranging over several kilometers, such as tunnels or roads, new requirements on the underlying models have become evident. These include the capability to represent substantially diverging scales as well as the applicability of the models to different or varying circumstances [9]. To decisively assist designers and engineers, those digital models need to support the efficient and consistent modeling and management of geometric objects on diverging scales.

One approach to representing spatially extended facilities with an adaptive semantic and geometric resolution is the use of multiple levels of detail (LoDs). This approach is well established in the domain of Geographic Information Systems (GIS) [28]. Previous research extends the LoD concept used in the GIS domain towards multi-scale representations of building information models, particularly used for the modeling of shield tunnels [9]. The main feature of the proposed concept is the preservation of the consistency across the different LoDs by applying parametric design techniques in order to define relationships and dependencies between geometric entities on different LoDs. However, one conclusion of this research is that the manual definition of the required parametric dependencies is a very complex, time-consuming and error-prone task, which could strongly benefit from automation mechanisms [6].

To address this challenge, this paper presents an approach to realize these automation mechanisms. It describes an automated detailing approach, which is based on the formal use of graphs and graph rewriting mechanisms. It further shows how procedural parametric geometric 3D-models based on two-dimensional sketches can be represented by graphs and how refinement steps can be realized through rule-based rewriting of these graphs.

The prospected benefit of this approach for end users is the reduction of the effort to manually define the consistency preservation dependencies. Doing so, it allows them to focus on the creative, conceptual and engineering aspects of the design process instead of time-consuming and repetitive modeling operations. Single-scale models can benefit likewise from the application of parametric modeling, since parameterized models can be easily adapted to different use-case scenarios and boundary conditions. The formal computer-interpretable description of a parametric design preserves the knowledge embodied in the respective manual tasks to build-up the model and allows their reuse in similar design scenarios. Furthermore, the modeling knowledge formal-

* Corresponding author.
E-mail address: simon.vilgertshofer@tum.de (S. Vilgertshofer).

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ized in graph rewrite rules may be applied to new scenarios with only minor alterations or even be generalized in a way that the rules themselves are intrinsically adaptable to different scenarios. Accordingly, we see the proposed approach as a contribution to the fields of knowledge-based engineering [43,31,1] and knowledge-driven design synthesis [35,26,46]. This proposed methodology is demonstrated by applying it to the modeling process of a shield tunnel. The model is detailed step-wise (as shown in Fig. 1) from the basic layout of the alignment up to a LoD containing several space objects of the tunnel as described in Borrmann et al. [9]. Based on the general introduction of a graph rewriting system designed to represent and manipulate elementary parametric and procedural modeling operations as well as the corresponding geometric objects, a set of exemplary rules describing the detailing process of the tunnel model is presented as proof of concept. In addition, the process of interpreting the graph for creating the *evaluated model* in a commercial parametric modeling system is described. A software prototype was developed to prove the feasibility of the developed approach.

The paper is structured as follows: In Section 2 related works in the scope of design support and automation as well as the theoretical background of the research at hand are outlined. Section 3 discusses the general approach of using graphs to represent a parametric 3D model. Section 4 focuses on the development of a specific graph rewriting system as a case study. The Section further describes a prototypical software tool, which is able to interpret the graph-based representation and create an actual 3D model. In Section 5, the general applicability of the approach is discussed in terms of its prospects and limitations at the current state of development. The paper ends with a conclusion discussing the development of our research, the major findings including known limitations and its possible generalization as well as topics for future research.

2. Related work

Benefits of the computer-aided generation of designs or models have been addressed by researchers in various aspects. This section gives a short overview of existing approaches and puts the presented approach in their context. It further presents the theoretical background of the proposed methodology in terms of parametric and procedural modeling, multi-scale modeling and graph rewriting.

2.1. Computer-aided model and design synthesis

Computers have been successfully used to support, accelerate and simplify the process of generating technical drawings and product models. CAD software is widely used and enormously valuable in the building sector and in mechanical engineering [11]. Its main purpose is to assist an engineer in his creative design work by resolving the disadvantages of paper based drawing, though. Design, however, is one of the most complex human tasks, as it requires the consideration of various constraints and conditions to obtain a satisfactory solution [3]. Therefore, a further step is the development of methods and tools, which actively support a designer by automatically generating whole sets of design variants or by the automation of repetitive and trivial tasks in the design process. As the concept presented in this paper contributes to this field of research, similar approaches, which also utilize graph representations, are discussed here.

In the field of Computational Design Synthesis (CDS), Helms [20] uses a graph grammar for the computational synthesis of product architectures. Design knowledge is captured in a port-based metamodel and the procedural design rules of the grammar. The dissertation and corresponding publications [21,20] show how the computational synthesis of a design solution space for automotive hybrid powertrains and for the generation of aircraft cabin layouts can be realized. Hoisl [23] presents an approach for creating a general spatial grammar system that introduces interactive definition and application of grammar rules in the scope of CDS. It aims at actively supporting a designer in the modeling process using mechanical CAD systems. The approach by Kniemeyer [27] in the domain of biology makes use of a graph grammar to design and implement a language to support the functional-structural modeling of plants.

Knowledge-Based Engineering targets the formalization of engineering knowledge to assist or automate routine design tasks, which are repetitive and time-consuming. Main contributions have been made by Cooper and La Rocca [13] as well as Stokes [42]. A comprehensive literature and research review that analyses 50 contributions is presented in Verhagen et al. [43]. With regard to the use of graphs, Chein et al. [12] introduced a knowledge representation and reasoning language based on conceptual graphs.

A method for using graphs in order to represent the shape and dimension of design variants was presented by Borkowski and Grabska [5]. Here, the conceptual design of bridges is used as an

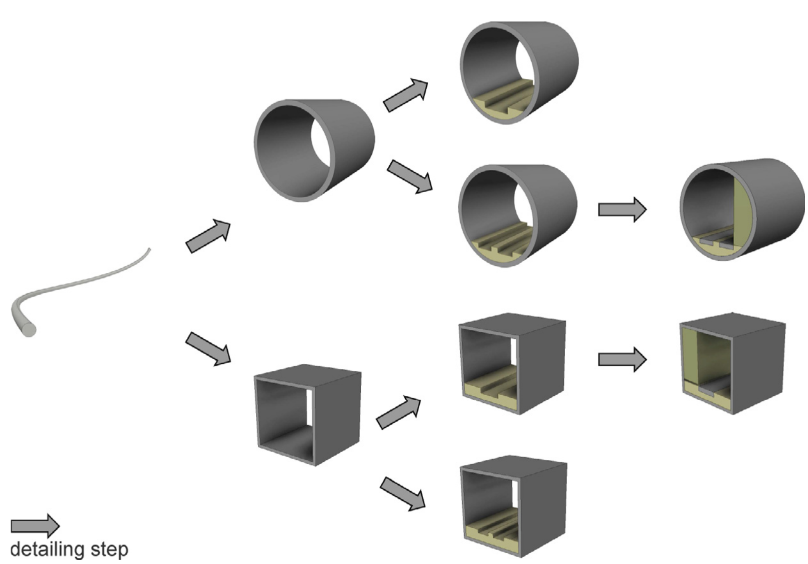

Fig. 1. Conceptual illustration of several detailing steps in a tunnel planing process. Dependent on the chosen rule different designs can be generated.