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Synchronous collaborative tunnel design based on consistency-preserving multi-scale models

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ABSTRACT

The planning of large infrastructure projects such as inner-city subway tracks is a highly collaborative process in which numerous experts from different domains are involved. While performing the planning task, widely differing scales have to be taken into consideration, ranging from the kilometer scale for the general routing of the track down to the centimeter scale for the detailed design of connection points. Currently there is no technology available which supports both the collaborative as well as the multi-scale aspect in an adequate manner. To fill this technological gap and better support the collaborative design and engineering activities involved with infrastructure planning, this paper introduces a new methodology which allows engineers to simultaneously manipulate a shared multi-scale tunnel model. This methodology comprises two main aspects. The first aspect is a multi-scale model for shield tunnels, which provides five different levels of detail (LoD) representing the different levels of abstraction required throughout the planning progress. The second aspect is a conceived collaboration platform, which enables simultaneous modifications of the multi-scale model by multiple users. In existing multi-scale approaches, where the individual representations are stored independently from each other, there is a high risk of creating inconsistencies, in particular in the highly dynamic collaborative planning context. To overcome this issue, the concept presented in this paper makes use of procedural modeling techniques for creating explicit dependencies between the geometric entities on the different LoDs. This results in a highly flexible, yet inherently consistent multi-scale model where the manipulation of elements on coarser LoDs results in an automated update of all dependent elements on finer LoDs. The proposed multi-scale model forms a well-suited basis for realizing the collaboration concept, which allows several experts to simultaneously manipulate a shared infrastructure model on various scales while using the different design tools they are accustomed to. The paper discusses in detail the principles and advantages of the proposed multi-scale modeling approach as well as its application in the context of collaborative tunnel design. The paper concludes with a case study of a large infrastructure project: a new inner-city subway tunnel in Munich, Germany.

1. Introduction

The built infrastructure – especially for transportation – is of crucial importance for today's highly developed societies, since it guarantees the mobility of its population and is a prerequisite for the constant stream of goods provided to industry and private households. This particularly applies to the transport networks of large cities, comprising rail-based public transport as well as a complex road networks. Due to the continuous growth of the population in the world's conurbations, the built infrastructure facilities are constantly being developed and extended.

The design and engineering of inner-city infrastructure facilities is a highly complex task, as numerous constraints and boundary conditions have to be taken into account. This includes the connection with the existing transport network as well as the technical characteristics of the infrastructure facility itself. As a consequence, a large number of specialists are involved which requires intensive and continuous collaboration.

Collaboration is usually organized in two different modi [1]: In the *asynchronous* form, information is exchanged between the different stakeholders without immediate feedback, i.e. the

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collaborative work is temporally decoupled. In the *synchronous* form, however, the participants work simultaneously and provide direct responses to proposed design modifications. While from a duration point of view, asynchronous collaboration is dominating the planning process, the synchronous phases play a more significant role: Here occurring problems involving the different parties are discussed and joint decisions are taken to solve them. For this reason, we focus on synchronous collaboration in this paper and present novel computational methods supporting it in the context of tunnel design.

An important peculiarity of infrastructure design is that widely differing scales have to be considered – ranging from the kilometer scale for the general routing of the carriageway down to the centimeter scale for the detailed planning of individual track nodes.

Today, these aspects are supported only to a very limited extent by currently available software tools for the planning of infrastructure projects. The majority of the projects still employ the conventional planning approach based on 2D technical drawings. This has a number of significant issues, including:

- The consistency between the different 2D plans (top views, cross-sections, etc.) must be preserved manually. As these 2D plans must be produced at multiple scales and on different levels of detail, their mutual consistency again has to be preserved manually.
- In consequence, all plans have to be manually checked and updated, when modifications are made.

These issues mean that the planning process is both laborious and error-prone, and that the engineers involved are forced to spend a disproportionate amount of time in dealing with minor administrative tasks and consistency preservation instead of being able to focus on the core engineering tasks.

This paper presents a comprehensive methodological approach for improving computer support for the planning of infrastructure projects that has the potential to overcome these limitations. In our investigations, we have focused on the following aspects:

- holistic application of 3D modeling techniques for the geometric design of the infrastructure project,
- development of a formal method for multi-scale modeling which supports automated consistency preservation between the different scales (each scale is represented by a dedicated level of detail),
- coherent coupling of semantic descriptions with multi-scale geometric models,
- techniques for supporting synchronous collaborative work on the basis of shared multi-scale models, including the development of locking mechanisms which allow engineers to work concurrently without disturbing one another and avoid to violate the consistency of the overall model.

The remainder of this paper is organized as follows: In Section 2 we introduce a new methodology for the inherently consistent multi-scale modeling of infrastructure projects which relies on the application of parametric modeling techniques for establishing dependencies between the different levels-of-detail. Based on this methodology, we describe a comprehensive data model in Section 3 with which it is possible to describe the primary track model, the multi-scale geometric model as well as the associated semantics in a three-fold data structure. This data model forms the basis for an infrastructure design collaboration platform which we describe in detail in Section 4. The paper concludes with a real-world case study: the second main subway track in Munich, Germany, which is currently in planning. We have applied our methodology to this project in order to prove its general suitability.

2. Inherently consistent multi-scale modeling

2.1. Overview

This paper presents a new methodology for creating, exchanging and storing multi-scale geometric models for infrastructure projects which explicitly defines dependencies between the individual levels of detail (LoDs). These explicit dependencies support automated consistency checks and even automated consistency preservation. The methodology relies on parametric modeling technologies [2], including the use of dimensional and geometric constraints for defining flexible 2D sketches, as well as the procedural definition of complex 3D models through the sequential use of geometric operations such as extrusion, transformation and Boolean operations.

Parametric modeling techniques facilitate a step-wise development of infrastructure models that evolve from a coarse LoD to successively finer LoDs, which precisely reflects well-established practice in infrastructure planning. Conventionally, when fundamental modifications at a coarse level are made at a late planning phase, such as the modification of the principal tunnel axis, the planners are forced to completely re-elaborate all related models and plans, e.g. the detailed tunnel geometry. By applying the methodology presented in this paper, modifications at a coarse LoD are automatically propagated to all finer LoDs, thus providing a means for an automated preservation of consistency and, at the same time, significantly reducing the effort required for re-elaboration.

2.2. Related work

The concept of multiple geometric representations on different scales is well known from the domains of Cartography and Geographic Information Systems (GIS). For example CityGML, an open standard for the storage and exchange of 3D city models based on GML, provides 5 different levels of detail [3]. The LoD concept in these application areas relies on the independent storage of individual geometric models on each level of detail (Fig. 1). As the dependency between the individual levels is not explicitly represented, inconsistency can easily arise. Nevertheless, for geographic applications the concept of independent LoD representations is well suited since GIS applications rely on rather static data sets, which are rarely subject to modifications.

Another important difference between the cartography/GIS domain and the infrastructure design domain considered here is the way multi-scale models are generated: In cartography, mostly a bottom-up approach is followed, i.e. detailed data is captured and abstracted to generate coarser representations [4,5]. In design processes, however, a top-down approach is followed starting from a coarse representation (e.g. the general course of a tunnel) and adding more and more details to create finer representations.

Taking these characteristics of planning processes into account, i.e. the strong dynamics regarding frequent model updates and the top-down design procedure, we present an approach to multi-scale modeling in infrastructure design, which provides both flexibility and robustness. To realize this, we propose the definition of explicit dependencies between the different levels of detail during the creation of the multi-scale model.

It is important to distinguish the *level of detail* concept elaborated in this paper from the *Level of Development* approach which has been introduced recently by the American Institute of Architects [6]. Though both concepts share the same acronym, there are important differences in the underlying semantics. The Level of Development approach is used to define the content, maturity and reliability of information provided by a building information model and serves as a basis for contractual specifications [7]. By