LOADt: Towards a Concept of Level of as-is Detail for Digital Twins of Roads

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Abstract. Building Information modelling has recently reached broader adoption in the AEC industry. The benefits of digital planning for process optimization in the construction phase as well as the improvement of building maintenance during the life-cycle of an asset, are the key drivers of digitalisation in the construction industry. Digital twins are gaining great attention at the same time, due to the requirement of smarter models for decision making and automation of varying tasks especially in the operation phase. In this work we introduce a multi-LoD-concept for digital twins of the road environment, to structure the different applications of a digital twin in a clear way. We also try to unravel the different and partially contradicting definitions of LODs that currently exist and create misconceptions which therefore hinder the faster adaption of digital methods in construction and maintenance, also slowing down progress in the development of digital twins.

1. Introduction

The benefits the correct use of digital planning has for process optimization in the construction phase as well as the improvement of building maintenance during the life-cycle of an asset, are the key drivers of digitalization in the construction industry (Vignali et al. 2021). The concept of Building Information Modelling exists since more than two decades, still the adoption of the BIM method in practice is slow due to multiple reasons. A major hurdle to the widespread use of BIM is the need for training on both sides, the client and the contractor. Especially for open BIM the complexity of processes and information exchange is constantly increasing. Amongst others, this results from the aim of using open standards like IFC, which however, are not yet available for all fields of construction.

For the road infrastructure domain, the adoption of digital methods for planning, construction and monitoring is developing slower, than in the building construction domain, making it possible to put thought into design decisions of interoperable standards for data modelling, in a much earlier stage. The learnings and current challenges in building construction and management can be adapted to develop a better connectivity of BIM for design and construction and BIM for management, as well as the development of digital twins of road infrastructure with BIM data serving as geometric-semantic foundation.

Considering the fact that road construction is the second-largest subdomain in construction in general, the adaption of digital methods for optimization and monitoring road networks is due and has great potential for improving efficiency in the process of road construction (Guo et al. 2022). In the case of road infrastructure, the large spatial extent of a construction site poses challenges for the digital representation. Since both, digital planning and also digital twinning of road assets are rather new subjects, there is a need for a concept to structure the digital representation of roads. Due to the fact that there exist various closely related, but differing concepts for the Level of Detail term, there are many misconceptions and misinterpretations of what is meant by LoD (Abualdenien and Borrmann 2022). This is especially important for the road infrastructure domain, since it is closer related to GIS than the building construction domain, which also introduces Level of Detail specifications from the field of GIS (Tolmer et al. 2017). Defining representations for different use cases like road asset management or even the various applications of digital twins, can support the development of a logically consistent definition, which in turn improves the applicability of the BIM method for the road domain, by clarifying similarities as well as differences between the concepts used in different applications.

Digital twins in general consist of four components: The first component of a digital twin is onsite sensor technology that transfers data to a data storage and analysis system, being the second component. The third component enables the interaction between the real world sensor system and the digital representation in form of a geometric-semantic model, being the fourth component (Jiaying Zhang1 et al.). When the interaction between real and virtual world is implemented only as a one way data stream from real world to virtual world, the system is called digital shadow, solely mirroring the real world environment without providing data flow back into the real world (Sepasgozar 2021).

The research question that we are addressing in this article is: How can the different requirements that various use cases place on the digital representation of a digital twin be structured in a transparent and meaningful way, so that a digital twin is able to represent several use cases simultaneously?

In the next sections, we will first introduce the LOD-concepts that exist in different domains to differentiate their scope, then we will introduce our concept for the geometric-semantic as-is representation for digital twins of the road, by discussing the concept with respect to similarities and differences to other concepts. Lastly, we discuss the next steps, for our concept to be applicable to the process of digital twinning in the road context. It can be noted that this contribution aims to be viewed as a first proposal to start discussions in the research community to collaboratively evolve the proposed idea into an applicable framework in the future.

2. State of the art: LOD/LoD Concepts

In the BIM domain, the notation LOD means "Level of Development", which is targeted towards different stages of development in the planning and construction phase of procedural digital models (BIMForum 2020). The geospatial information modelling (GIM) domain however, defines LoD as the "Level of Detail" of digital (city) models. Since the road infrastructure domain is closely related to both BIM and GIM, these terms have to be clearly differentiated (Herle et al. 2020). In (Abualdenien und Borrmann 2022) the authors analyzed 58 international LOD guidelines between 2005 and 2020. It turned out that LOD and LoD for "Level of Development" and "Level of Detail" were interchangeably used in BIM. However, "Level of Detail" in GIS stands for the amount of detail in the geometric representation, while "Level of Development" in BIM defines the conceptual stage of a product, quantifying the reliability of some representation. In this way a road can have a "Level of Development" of 500 indicating that the conceptual stage is 'as-built', still the road can be represented in a "Level of Detail" of 200. The Level of Detail was first introduced in computer graphics to quantify the geometric complexity of a 3D object, in this domain the focus lies on efficiency in model representation, where, depending on the point of view peripheral objects are rendered with a lower LoD. (Reddy 2001)

2.1 LOD-Concepts for Design and Construction

The method of BIM was first established for design and construction. That is why many actors in the field of construction still only refer to a digital model being used and continuously refined and enriched with information in the course of the planning phase. In terms of the process orientation in the planning phase, a model is supposed to change in shape and in the density of information attached to it over the course of planning. Such a BIM is called a procedural model (Biancardo et al. 2020). In every exchange scenario between stakeholders in the planning process, the “Level of Development” of a model has to be specified in order to ensure the minimum required information is present in the model for being able to perform the next step in planning. The “Level of Development” is the most prominent concept in BIM for design and construction, since it targets the exchange requirements during the BIM process itself. It evaluates the maturity of a digital construction model and consists of six individual levels.

The “Level of Development” definition can be further differentiated into LOG for “Level of Geometry” concerning the granularity of geometry and the LOI for “Level of Information”, which concerns the alphanumeric or attributive information of a model. As an addition LOIN, the “Level of Information Need” was introduced in 2020, which better accounts for information need at a certain exchange scenario in the planning phase. Following DIN EN 17412 the LOIN is defined for specific exchange scenarios and is therefore not necessarily bound to fixed levels.

Whether it is sensible to define the “Level of Development” for whole models or only based on single elements, is crucial, since for most steps in the design process only a subset of the elements is important. In addition, some elements like windows will maintain the same “Level of Development” from some stage on, while other elements might consistently change. By dictating a consistent “Level of Development” over all elements, the model may contain many details that are out of scope for a specific exchange scenario.

2.2 LOD-Concept for Road Management and Maintenance

The use of BIM differs between design and construction and operation and maintenance in terms of available information and process orientation. The digital model used for management can only be an as-is/as-built model, ideally reused from the design and construction phase (Becerik-Gerber et al., 2012). However, structures built without digital information aggregation are susceptible to information loss, making it challenging to define the LOD for such structures. The potential for more efficient management of the built environment lies in linking both use cases of BIM. Abualdenien and Borrmann (2022) highlight misunderstandings of LOD terms and the need to establish a concept that considers the likely scenario of lost information. Becker et al. (2019) proposed the LOAD definition for the "Level of As-Is Documentation," which links construction and management stages and provides context for the terms' use. The LOAD comprises LOAG, LOAI, and LOA, denoting "Level of as-is Geometry," "Level of as-is Information," and "Level of Accuracy." LOAG has four levels (LOAG10, LOAG20, LOAG30, and LOAG40), while LOAI is not differentiated into different levels, but rather by specific use case, similar to the LOIN definition. Overall, linking design and construction with operation and maintenance has significant potential for more efficient built environment management.

2.3 LoD-Concept for Digital Twins

GIM, is mostly used for documentation, analysis and visualization of the existing world, therefore the concept of “Level of Development” is not applicable to the GIM domain. Instead, in GIM LoD denotes “Level of Detail”, in particular concerning the geometric complexity of representation. In computer graphics, the “Levels of Details” are quantified over the number of vertices used to represent some 3D object. The “Level of Detail” used in the GIM domain is closely related to our application, where we aim at representing a digital road model in different geometric-semantic representations. The basic assumptions are similar, in a way that all necessary information has to be available before generating a model and the scope is not to update the model to become closer to something that can be built, but to define a certain subset that fits the demand of a specific use case in the best possible way. The geometric representation serves the purpose of enabling the reduction of unnecessary details, that solely slow down the application. However, instead of only focusing on the geometry, our concept also involves the semantic side of a model, meaning that we also specify the classifications of elements in a hierarchical way with rising semantic granularity. Though fundamentally aiming at a comparable use as BIMs for asset management, digital twins of the road environment need additional specifications concerning their semantic structure as well. Further central components of the concept involve the geometric uncertainty (accuracy of geometric reconstruction) as well as the semantic uncertainty (correctness of the classification). These two measures are intended to take account of the fact that as-is models show more or less inevitable imperfections, because they are based on uncertain input data. These modifications are necessary since our concept has to be applicable to models derived from reality capturing, as well as models developed in the planning phase that are then reused as foundation of a further development of a digital twin of an asset. It becomes obvious that aspects of GIM and aspects of the BIM definition of LoD/LOD respectively have to be combined to a certain degree to develop a concept for digital twin representation.

To conclude the differentiation of the basic terms of LOD, it can be said that “Level of Development” and the connected terms LOG and LOI are defined concerning the process of continuous refinement and enrichment with information for planning a product, while “Level of Detail” accounts only for the geometric representation and is established in GIM and computer graphics. There exists also a “Level of Documentation” concept for as-is structures with the focus on use cases, where the built structure has to be captured, e.g. via scanning methods, first. Our concept for digital twins must accommodate both existing digital models from the construction process and new models from reality capture such as laser scanning and photogrammetry. To do this, we must map these models into specific layers and determine what additional information is necessary to fit each layer's demands.

3. Methods: Level of as-is Detail for digital twins– Our Concept

In this section, we will introduce our “Level of as-is Detail” concept for digital twins of road assets. As previously shown, there are many different definitions of Level of Detail as well as for Level of Development. Since digital twinning normally deals with built assets, the basic “Level of Development” definition is out of scope for our concept. However, in our specific aim the idea is to construct the best possible geometric-semantic representation of a road in order to enable monitoring, analyzing and performing actions in the digital twin that interfere with the real world environment. We, however, not only aim at geometry as single aspect of the representation of the twin, but also on the semantic aspect in terms of correctness of the semantic class, that can be assigned to an entity as foundational information to enable linking information in use cases.

It is clear that there is no single representation to fit the diverse use cases of a digital twin. Hence, for each use case, the specification of the optimal geometric-semantic representation has to be defined inside a framework with enough variability to fit their specific needs. Additionally, a shortcoming of some existing concepts in general, is the definition of LOD on the model level as opposed to the element level as stated by (Abualdenien and Borrmann 2022). Applying this constraint to our concept results in the trade-off between freedom of representation and simplicity of a model. On the one hand, giving every object an own representation will result in potentially unique setups for simulations, making it nearly impossible to replicate them, additionally if every object can have an own representation the

“Level of Geometric Representation” as we call it (following: LoGR) has to be specified for each single object. On the other hand, fixing all objects at a similar LoGR results in suboptimal models for the use cases they were generated for. Combining structure and comprehensibility into one concept that is suited for all possible use cases, is no trivial task. Keeping the purpose of a digital twin in mind, we deal with that trade-off by defining groups of objects that behave alike and assign one LoGR to each group, which we call functional units, while the LoGR can be shifted between those units. We therefore define functional units that are likely important as a collective for specific use cases, while being negligible for others.

As shown in (Abualdenien and Borrmann 2022) there exist several attempts to define new concepts resulting in rising confusion and complexity. Defining a concept for a new domain will always result in rising complexity, still to minimize the confusion potentially added to LODs, we call our concept LOADt thereby branching off of the typical wording of other LoD/LOD concepts. Recently, the CityGML 3.0 Conceptual Model has been proposed augmenting the LoD concept of CityGML 2.0 (Kutzner et al. 2020). Especially the transportation complex was taken into account in the new concept, introducing three Levels of Granularity. On granularity Level 1 the whole area of the road environment is defined as single object, Level 2 differentiates the carriageways, green areas and sidewalks, whereas Level 3 further splits carriageways into single lanes. The paper proposes adapting the concept of representing roads as linear segments, areal, and volumetric models, as introduced by (Beil et al. 2020), to other objects like road signs, which can be represented as points in a linear model or as 3D objects in a 3D model. The CityGML3.0 concept of Level of Granularity, which hierarchically splits classes into more precise subclasses, is used to define the semantic depth of an object, where the granularity is directly bound to the form of representation. To allow for highly detailed geometric representations, even with a low semantic diversity, the authors detach the geometry and semantics, which is similar to the CityGML conceptual model but applicable to all road assets. This approach considers a more complete differentiation of relevant classes concerning the road environment and allows for more versatility in potentially generated models. The proposed concept is particularly suitable for use cases such as pavement monitoring, where a highly detailed surface representation is essential, while it is less important to differentiate object classes concerning road furniture. We introduce the concept of "Level of Semantic Granularity" (LoSG) as the semantic aspect of the proposed approach. This design decision requires defining a taxonomy for structuring road assets in a hierarchical manner, enabling the predefinition of possible semantic classes at different LoSG levels. The class taxonomy was derived from various relevant standards for digital representation of roads, including CityGML, the German road asset catalogue OKSTRA, and IfcRoad.

Our approach links LoSG and LoGR to enable different representations of the same object class and differentiation at the semantic level for the same representation. For example, in obstacle detection for vehicles connected to the digital twin, the semantics of a speed limit sign in terms of its class or implications to normal traffic may not be relevant. Thus, the LoSG would be Level 1 (road furniture), which would define a stop sign and a speed limit sign as the same class. However, the LoGR of these assets would still be high in the use case at hand, so the representation of the sign would be as precise as possible to the real geometry, enabling a realistic scenario for the simulation. Contrary to a relevant asset, irrelevant assets can simply be removed from a specific scenario, through a LoGR of 0. Lastly we adopt the Level of Accuracy from the works of (Becker et al. 2019) to our concept, since for most cases, in order to create a digital twin of existing roads, they first have to be captured using reality capturing techniques, making it necessary to quantify the geometric accuracy of the model. Since the process of capturing a road segment and performing semantic segmentation in order to extract objects with varying granularity also introduces semantic uncertainty, we split the “Level of

Accuracy" into "Level of Geometric Uncertainty" and "Level of Semantic Uncertainty". The "Level of Geometric Uncertainty" (LoGU) specifies the accuracy of location and shape of the captured asset, while the "Level of Semantic Uncertainty" quantifies the uncertainty of a particular road asset belonging to a semantic class. The "Level of Semantic Uncertainty" (LoSU) is linked to the LoSG hence it forms a criterion for evaluating the meaningfulness of differentiation of assets into higher granularity. This connection arises from the hierarchical structure of the LoSG. Given the complexity of object classes rises in each consecutive LoSG, the quality of the semantic segmentation of classes on a higher LoSG will be less certain, than of classes in a lower LoSG. Additionally, there might be use cases, where the correctness of a semantic class is extremely important, while in other use cases it is not. With the incorporation of this kind of quantification of the uncertainty of class, we introduce a new dimension to optimizing models for specific use cases. An overview of the introduced terms making up our concept, which as previously discussed, is derived from a combination of different standards as well as our own modifications, is depicted in Figure *1*.

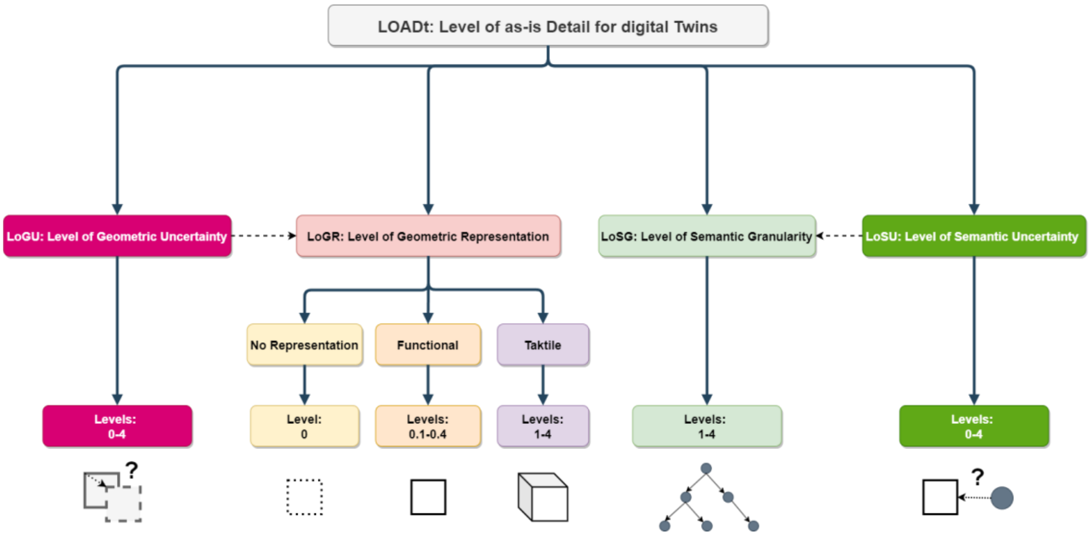

Figure 1: LOADt-Concept for Digital Twins of Roads

The LoGR stands for the geometric representation of the model. The general question arises whether it is sensible to, apart from the actual form of geometry, assign some technical type of geometric representation to a specific LoGR like for example the boundary representation. We come to the conclusion that, since the possibilities of the technical type of geometry representation are mostly limited by the relevant standards, the concept itself should not limit the form of representation in any way, so this aspect of the representation remains open and specific to the use case at hand, following the IFC standards approach of enabling diverse types of representation for the same object. In that way, the LoGR defines the geometrical complexity in the representation of an object, which is depending on the application for which the model is to be used. The LoGR defines the geometric complexity on a scale between "No representation" for the minimum boundary and point cloud derived meshes of each object as maximum boundary. Depending on their dimensionality, we differentiate three groups of representations. No representation is denoted as LoGR 0 and can be interpreted as 1-Dimensional data in form of attached information, where use cases are considered, where a specific geometric representation is not required. In the road domain the transportation network is often defined in a 2-Dimensional network, to also consider 2D representations as potential option, we define the functional representation with Levels 0.1-0.4. Especially for use cases where the logical connection of road segments over a great spatial extent is of interest, the representation of roads defined by their centerlines in LoGR0.1 is computationally cheap, but able to hold the same semantic information as LoGR1 does. The tactile group defines the standard 3-dimensional representations, that are typically used in BIM use cases. Both groups, the functional and the tactile group behave similarly for changing LoSG. The difference mainly lies in the way of representation. This logic was partially derived from the work of (C. Beil & T. H. Kolbe 2017), who modified the LoD-concept in CityGML 2.0, by separating areal and linear representations, this consideration was then integrated into the LoD-concept of CityGML 3.0 (Beil et al. 2020). We use this idea on an abstract level, since our concept differentiates the representation as well as the semantic granularity. Our representation shall be independent of the semantic depth, which is not the case for the concept in CityGML. In the functional representation, objects are either represented as points for objects like road signs or potholes or as lines for guardrails or the road itself. We define the LoGRs of the functional class as follows: On LoGR 0.1 only the centerlines of the road segments according to their granularity or centerlines of lengthy objects like pipes are represented, while other objects are represented as a point location, with respect to their center of mass of the object. On LoGR 0.2 the centerlines, as well as the boundary lines are represented for line objects and for point objects, their minimum 2D boundary is represented as polygon. On LoGR 0.3 all objects are represented as 2D structures from the top-down view. LoGR 0.4 represents objects in 2,5D, which shall mainly serve visualization purposes. An example for the different functional LoGR on a fixed LoSG 3 are shown in Figure *2*.

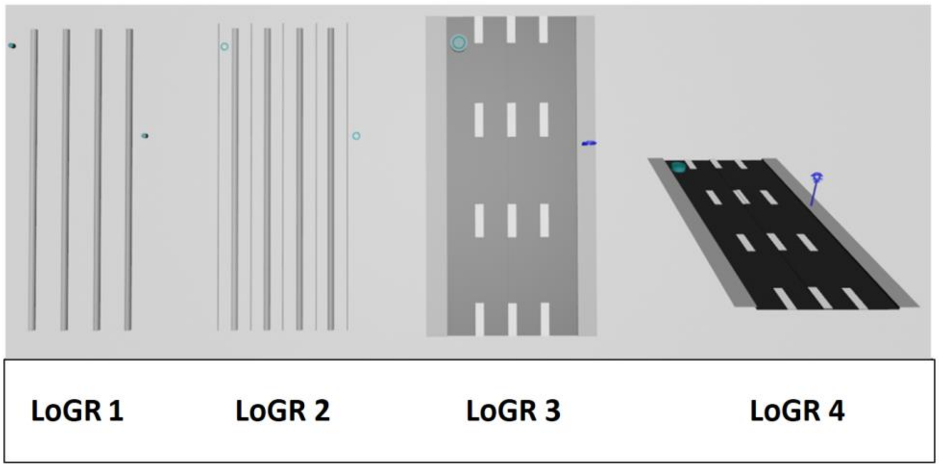

Figure 2: Schematic Example of Functional Level of Geometric Representation of Road Space Functional Unit at LoSG 3

We define the tactile LoGR as follows. On LoGR 1 an object is represented as a geometric primitive with the minimum boundary volume. On LoGR 2 the representation follows a combination of multiple geometric primitives, on LoGR 3 the representation follows fitted pre-modelled structures similar to an as-planned digital model and LoGR 4 is represented as a surface mesh derived from instance wise segmentation of an underlying point cloud which is the only representation true to deformations for the as-built/as-is case. For the different “Levels of Semantics”, we add Level 4 for the road cross-section and hidden objects like piping for drainage systems in the near field of roads to the existing concept of CityGML 3.0. We furthermore define five Levels of Geometric Uncertainty which are adapted from the Level of Accuracy in (Becker et al. 2019), but transform the accuracy specifications to the outdoor domain, where due to the spatial extent of structures the accuracy has to be evaluated differently than in indoor environment. The “Level of Semantic Uncertainty” accounts for the process of capturing and semantically segmenting object classes from survey data. In this process, the output holds a certain degree of uncertainty due to the methods involved. A perfectly calibrated segmentation model will in most cases not reach 100% accuracy on unseen data. In order to quantify the uncertainty introduced in model errors and miscalibration of a model, the LoSU is necessary, since it holds information on the potential risk of erroneous object information. As example, if a model holds information on the driving rules of a road segment through the classified road signs, the LoSU has to be high, hence if a stop sign was labeled a speed limit sign this error would pose a high danger compared to the same setup in the context of obstacle detection where the main goal is avoiding a crash. It is also likely that object classes in a higher LoSG will be segmented with higher uncertainty. Additionally, if the geometry is derived from segmented point clouds, the LoGU of the chosen representation also depends on the LoSU, therefore it might be useful to initially choose the LoGR depending on the LoSU as well, since errors in the semantic class will propagate to errors in the geometry. Choosing a lower LoGR accounts for a higher uncertainty of the object shape and is bound to a coarser representation, in which an object is more likely to still be valid. Figure *3* shows the different components in our concept on the example of a road sign. In LoSU and LoGU, Level 0 is defined as "Unspecified" for cases of unknown uncertainty. Since the thresholds for LoGU and LoSU have not been validated yet, Figure 3 shows only a conceptual definition of the geometric ranges and semantic certainties in each consecutive level. These values will likely change in the course of a case study, that we will conduct in future work, to validate our concept for practical use. The main purpose is to show how the levels in LOSU and LoGU will behave, as it can be noted that higher levels in LoGU are defined with higher accuracies, while higher levels in the LoSU are defined with a higher required certainty of a correct semantic class.

	LoSG	LoGR	LoGU	LoSU
Level 1	Road Furniture		30 cm – 10 cm	85%
Level 2	Road Sign		10 cm – 5 cm	92%
Level 3	Stop Sign		5 cm – 1 cm	96%
Level 4	/		1 cm – 1 mm	99%

Figure 3:Components of LOADt Concept at Example of Stop Sign

By analyzing different standards for modelling the road environment, we defined functional units for the LoSG. These functional units of classes are road space, road furniture, civil structures, traffic and vegetation. By separating the class taxonomy into separate groups, we enable some degree of freedom for having different LoSG in one model, but reduce the complexity of a model, thereby solving the trade-off discussed in section 2. Since the groups represent functional units, it is likely that the necessary granularity of classes inside the groups behaves similar over most use cases, minimizing the potential shortcomings of defining the LoSG on a higher layer than on individual elements. These groups can be replaced by other class hierarchies for a specific environment, which makes our overall concept a modular framework, that can be applied to any other domain, where digital twinning is of interest. Still, this taxonomy has to be developed according to the relevant standards in the specific domain. To illustrate the behavior of the different LoSG within our module, Figure *4* shows the four LoSG of the road space functional unit in tactile LoGR 1.

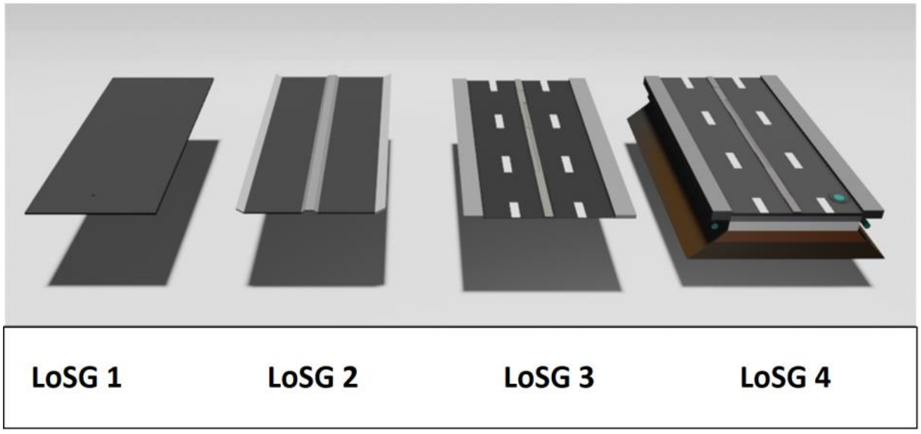

Figure 4: Schematic Example of Levels of Semantics for Road Space Unit for Tactile LoGR 1

In the course of developing the general concept, we conducted a requirement analysis of different use cases for the digital twin of the road. Regarding the representation, the use cases can be structured into such with requirements towards local geometric detail such as pavement management using finite-element simulation, where the road surface and substructure are required as precise geometry, which must be true to deformation. On the other hand, there are use cases that cover a large scale, comparable to intelligent transportation systems (ITS), where the geometry is less important, but rather the road network and topological connections in the form of nodes and edges. These two examples define the outer boundaries for use cases we cover with our concept, that are to be provided with representations inside a digital twin system.

4. Conclusion and Outlook

To answer our research question: The overall idea of our concept is that given a diverse set of input data, stored in a database that represents the as-is state of a road, we can create models from subsets of the available geometric and semantic data to perform a use case With our concept we want to take a first step towards a common understanding of different geometric-semantic as-is representations, for specific use cases, depending on individual demands.

In the process of generating a digital twin, it might be important to quantify the uncertainty of semantic correctness, but the question is whether it makes sense to have different levels for that, or rather couple the uncertainty with the representation derived from the semantic segmentation with suitable safety of correctness directly. This would simplify the concept, but also remove the option to freely fit an individually sufficient certainty to a use case. The question is whether there are use cases, where the certainty of an object class belonging to a specific class in a higher LoSG is negligible at some threshold. These thresholds for semantic uncertainty as well as the ones for geometric uncertainty have to be defined in advance and can differ significantly for different use cases. In the current stage, we define LoSU and LoGU as initial step, having in mind that it may change or further develop in the further course of the work.

In future work we aim at aligning the different standards for digital modelling of roads with our LOADt-Concept in order to establish the link between the database of a digital twin and specific use cases, that generate data and collect information on the real world road. This will create the opportunity of defining best practice processes to perform specific tasks with the digital twin and simplify the interoperability between the standards, by utilizing the concept as structure for the middle layer between the available data and a specific model defined in a specific standard. Our goal for ongoing research on the subject of digital twins for roads, is to establish the proposed link between the different domains that are relevant for creating a digital twin. Utilizing this concept, we will develop a framework for automatically generating geometric-semantic as-is models that fit specific use cases. In this way, we will be able to provide best fitted models to different stakeholders that can then support the information enrichment of the digital twin of the road.

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