GIS TECHNOLOGY

The concept of level of detail in 3D city models

PhD Research Proposal

Ir. Filip Biljecki

GISt Report No. 62

TU Delft Delft University of Technology

Challenge the future

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Summary

Level of detail (LoD) is a concept available in various disciplines from computer graphics and cartography to electrical circuit design. For GIS practitioners, the discipline where level of detail is most relevant and well known is 3D city modelling.

While present LoD paradigms, such as the one found in CityGML, fulfil the requirements of many applications, there are significant shortcomings: the levels are discrete and their number is limited, potentially there is inconsistency between different LoDs, the paradigms do not take into account the application and user's needs, and redundancy is present in virtually all parts of the modelling-storage-query-visualisation workflow.

This PhD research aims to improve the concept of level of detail in 3D city modelling through (1) its formalisation in a definition, (2) modelling it as a spatial dimension, i. e. in a space-scale hypercube, (3) definition of contexts with use-cases which take into account the environment in which level of detail are needed, and (4) generation of pseudo-continuous levels of detail which are customised for an application or for general use.

This research will be conducted over a period of 48 months with a dissertation as its principal deliverable.

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Acronyms

ADE	CityGML Application Domain Extensions
CAD	Computer-Aided Design
DTM	Digital Terrain Model
GIS	Geographic Information System
LoD	Level of Detail
R&O	Result and Development Cycle for staff member of the TU Delft
SLoD	Sub-Level of Detail
UML	Unified Modelling Language
VRML	Virtual Reality Modeling Language

Chapter 1

Introduction

1.1 Motivation

Level of Detail (LoD) is an important concept in 3D city modelling which define the degree of abstraction of real-world objects, primarily designated to use an optimum amount of details of real-world objects according to the user's needs, and computational and economical aspects. However, despite the widespread usage of LoD, there is a number of shortcomings, and in 3D city modelling the topic is not yet researched throughly.

For instance, the concept of level of detail vary in 3D city modelling and it is not officially standardised. There are standards such as CityGML (OGC), however, their concepts significantly differ from each other and there is no consensus on LoD: it is not unambiguous what an LoD is in 3D city modelling, and there is not a single and widely-accepted LoD paradigm in 3D city modelling. There are no guidelines, and it is not clear what drives the LoD, and technical specifications such as accuracy and precision requirements are not addressed for a certain level of detail. In short, the philosophy and the criteria that drive the level of detail in 3D city modelling are vague and undefined.

From a computer graphics perspective, continuous level of detail, and mixed scale (perspective-view) are not investigated in Geographic Information System (GIS) for 3D city modelling, and current implementations of 3D city models (e. g. CityGML) are limited to a certain number of discrete levels of detail.

Considering the applications, the number of LoDs in most standards is limited for a number of applications, and there is no LoD concept which adapts based on the application. Further, the acquisition, storage, manipulation and generation of multiple and different levels of detail is usually redundant, inconsistent, not linked, and it requires separate operations, which in practice yields high costs. There are obvious computational challenges with current LoD approaches, primarily redundancy.

Addressing and resolving these issues have both academic and business advantages.

1.2 Research questions

The PhD project will investigate the LoD paradigm, the integration of the different LoDs of a 3D city model into one consistent 4D data model, and the creation of LoDs using algorithms that take into account the user's and application's needs.

The main research question that this research will answer:

> How should we treat, model and include the Level of Detail (LoD) in 3D city models, and what implementations are possible?

The method should take into account consistency and removing redundancy. The accompanying research sub-questions that are related to this research, and will be also answered are:

1. How are LoDs currently integrated in 3D city models and how are they used? What is a LoD in the frame of 3D city models?
2. What is the current school of thought behind LoDs in city models? What are the types of LoD? What are their limitations?
3. Can we define our formal definition for the Level of Detail (LoD) that takes into account a theoretical background, mathematics, and linguistics, and that is consistent to current definitions?
4. How should we treat the scale in the frame of 3D city models? What are the criteria in defining the abstraction in an LoD?
5. Can concepts used in cartographic generalisation, such as vario-scale, be applied in improving the concept of LoD?
6. Can we integrate the scale as the 4th spatial dimension? Can we create a 3D+Scale hypercube? How?
7. Can texture and the interior be efficiently integrated into the new concept?
8. What are the criteria that should define a level of detail?
9. How do different LoDs affect different applications? Are there major differences in results of analyses?
10. Can we create an LoDs that takes into account external variables such as the application, computational aspects, and user needs?
11. Can we create continuous LoDs or it is more feasible to a number of discrete LoDs?

1.3 Scope of the research

This research is about the general concept of the scale in 3D city models, with a practical implementation. The focus will be on LoD from a GIS perspective. The research will not deal or will have a limited scope with:

- Interior (i. e. furniture). While interior is included in one of the research questions, the vast majority of 3D city modelling applications is 'outdoors', where the interior geometry is not necessary. Hence, the interior can be considered as an addition for a few specialised applications. Furthermore, current trends such as the development of the IndoorGML standard indicate that standard-wise and application-wise the interior geometry is conceptually separating from the exterior. This research will deal with the interior as long as it can be integrated in the developed paradigm without significant excess work, and requiring the development of additional concepts.
- Textures from the image processing view. Texture is an integral part of 3D city models, but some of its concepts can be separated when considering that they are more connected to image processing techniques rather than GIS.
- Semantics, due to the fact it is not the focus of the research project. However, it will deal with semantics of LoD concepts and maybe also of geometries.
- Level of detail from a computer science (computer graphics) approach (e. g. mesh simplification), but some concepts may be investigated and borrowed.
- Level of detail from the 3D generalisation approach, but the latest developments in this field will be overviewed and will be taken into account.
- A specific data format implementation and conceptual model, e. g. CityGML, but such can be used to prove the concepts that are developed in this research.
- Subsurface objects, such as the ones found in geology, geo-technical data, utility cadastre, will not be included in this research.

This research will deal with the common (topographic) objects found in 3D city models, such as buildings, forests, lakes, rivers, roads. Most of the examples will be concentrated towards buildings, though, as they are the most prominent type of objects.

1.4 Positioning within the project

This research is a part of the project 5D Data Modelling: Full Integration of 2D/3D Space, Time and Scale Dimensions. The aim of the research is to integrate the multi-dimensional characteristics of geographic data, i. e. 2D/3D, time and scale (also indicated as LoD, resolution, or granularity) at a fundamental level of data modelling (Stoter et al., 2012; van Oosterom & Stoter, 2010).

The work of studying higher dimensional spatial data models, data structures and operations (Arroyo Ohori, 2011) will be used, and a collaboration with its author will be established.

1.5 Relation to other projects

Vario-scale geo-information (funding provided by an STW grant with project code 11185) is a closely related project executed at the same section, dealing with the integration of scale as a spatial dimension in cartography. It involves the work of Peter van Oosterom, Martijn Maijers, and Radan Šuba (van Oosterom & Meijers, 2011, 2012a,b). The possibility to establish a link between this research and the Vario-scale geo-information project will be investigated during the research.

Disaster management is another important topic at the GIS technology section, and not directly related to this research. However, a link can be established through practical consideration and application of developed concepts in the usage of 3D city models in disaster management.

At this phase there is no plan to connect this research to projects of other departments outside TU Delft. This possibility depends on future developments.

1.6 Structure of this report

This document is divided into five chapters:

1. The current chapter introduces the project, the research questions, and the proposal, ending with the overview of the terms used in the title.

2. The second chapter (p. 5) introduces the main concepts relevant for this research, and provides a literature review of the state of the art of the LoD paradigm, and related topics.

3. The research is proposed in the Chapter 3 (p. 27): approach, goals and research objectives, methodology, and the benefit of this research.

4. Chapter 4 (p. 41) deals with practical aspects of the project, e. g. milestones and involved parties. It also includes information and plan dedicated to the Graduate School, as the researcher is its student.

Chapter 2

Related work

This chapter provides a literature review of the concepts related to this research, and practical aspects. The theories of 3D city models, and general aspects about scale and LoD are overviewed in:

Levels of detail in various disciplines are described in

2.1 3D city models

2.1.1 Introduction

Stadler & Kolbe (2007) define 3D city models as digital representations of the Earth's surface and related objects belonging to urban areas. Virtual 3D city models are applied for an increasing number of tasks related to environmental simulations like noise mapping, training simulators, disaster management, architecture, and city planning. An example of the visual representation of a 3D city model is shown in Figure 2.1.

The terms in the definition should also be separately defined:

3D denotes three-dimensional GIS data in which all dimensions are properly and geometrically defined. Concepts which include spatial data in 3D to a limited extent or as pseudo-3D view, such as 2.5D are not considered as 3D in the sense of this research.

City implies coverage in urban areas, however, 3D City Modelling is not limited to them, hence the term is broader. They are also suitable for rural areas (e. g. 3D topography). However, most of the applications and data available are city-related.

Model is a computer representation of an object as a result of a process of modelling. A model can be rendered on a 2D computer screen, or be physically created (printed).

Figure 2.1: An example of a 3D city model. Courtesy of virtualcitySYSTEMS.

The main applications of 3D city models are (Blaauboer et al., 2012):

- Calculation floodplains
- Drainage Calculations (urban water)
- Urban planning visualizations
- Spatial planning in early stage
- Issuing of building permit
- Noise and environmental analyses

- Insolation studies
- Design processes for urban and regional development
- Review of urban design
- Simulations for public order and safety
- City promotion (graphically, through model and interactive)
- Games
- Volume Determination of buildings for property tax
- 3D Land Registry
- Brokerage (preselection of housing by customers)
- Telecommunications (GSM positioning transmitters)
- Urban heat analysis
- Wind simulations
- Civil engineering work preparation

A notable synonym of 3D city models is Virtual City Models, and the usual shorthand is 3DCM. It is also important to note that 3D city models are an ambiguous term since they also include physical (materialised) 3D city models. However, in the GIS context, there is usually no confusion between the two, so this document will use the term 3D city model for virtual 3D city models, and physical 3D city models will be denoted specifically.

2.1.2 Selected use-cases

This research will take into account two applications as use-cases and examples of the application of 3D city models. The following use-cases were taken into consideration, and are listed by preference (the first two are selected, while the remaining one serves as an alternative):

- Solar potential

  3D data (both 3D city models and laser point clouds) are used worldwide for assessing the solar potential of rooftops in urban areas (Kassner et al., 2008; Redweik et al., 2011). The solar irradiation is estimated from the tilt, direction, and area of a rooftop, for the purpose of assessing the potential yield of solar cells.

  This application is interesting because a LoD in which a fine roof structure is available is required, but on the other hand the details on the facade (i. e. openings) are irrelevant since photovoltaic cells are virtually always placed on roofs. However, openings on the roofs (e. g. windows) should be available as well, since they lower the area on the roof on which a panel could be placed, so the openings should be distinguished based on the location on a building.

Other categories of objects should also be distinguished with respect to the importance, for instance, trees which may cause a shadow are more important than waterbodies which do not affect the solar potential of a rooftop (Hofierka & Zlocha, 2012).

- Personal navigation

  Recent personal navigation solutions include 3D city models for easier and more realistic orientation.

  Regarding the LoD, there are some aspects that should be taken into account, and make this use-case interesting for this research:

  – Landmarks and buildings closer to the route are more important than the others, and should have a finer detail (e. g. texture), while more distant objects can be omitted in the visualisation or shown in the coarsest LoD.
  – Objects of different types have different navigational value, e. g. a building of type 'restaurant' and 'brand' McDonald's offers more navigational cues than a block of gray, anonymous residential buildings (Nedkov, 2012), hence semantic properties are of significant importance.
  – The selection of a LoD is also speed-dependent, e. g. when a user travels with a high-speed, it is not important to use fine LoDs

  The combination of the above factors make an interesting use-case to consider in this research.

- Noise mapping

  GIS is indispensable in noise mapping (de Kluijver & Stoter, 2003). By using 3D city models it is possible to assess the propagation and impact of noise on the environment (Stoter et al., 2008), which is especially important in urban areas (noise pollution). Delft was already a site of noise pollution assessments, e. g. see the analysis of Kurakula & Kuffer (2008).

  In this application, again some details are more important than the others (e. g. material of the building), while others are irrelevant in the analysis (e. g. texture).

  Meijers et al. (2012) state that noise modelling in 3D would benefit from having more detail available close to the source of the noise, while further away less detail is needed, since the farther buildings have less influence on the propagation of noise. This is an interesting example of using mixed-LoDs in the same scene, where a function which takes into account the distance, i. e. the distance from the source of the sound is a factor in the context.

Other alternative, less prominent, but still interesting use-cases can be found in using 3D city models with air quality data (José et al., 2012), wind modelling (Amorim et al., 2012), and urbanism.

While developing the use-cases, it will be important to use the data of the same spatial extent for comparison reasons.

2.2 Scale and level of detail

The central topic of this research, the concepts of scale and of level of detail are not only found in Geomatics, but also inside many other disciplines, what contributes to the vagueness and looseness of both terms, and depends on the context.

To Geomatic engineers and cartographers, the scale of map is well known, and Thompson (2009) provides a good overview of the term: The scale of a map is the ratio of distances on paper to the distances of the real world objects being mapped. For example: a scale of one to 250 000 indicates that 1 cm on the page is equivalent to 250 000 cm (or 2.5 km) on the ground. The term "small scale" is used for cases where a small amount of paper is required to represent a region. Large scale requires a larger sheet of paper. Thus 1:250 000 is small scale, 1:2500 is large scale. Figure 2.2 shows an example of a scale bar of a map.

The scale is more applicable to materialised representations such as paper maps, rather than spatial data in a computer representation. Through an analogy, in 3D city modelling, the scale is applicable to physical models. However, the scale is present in computer as well.

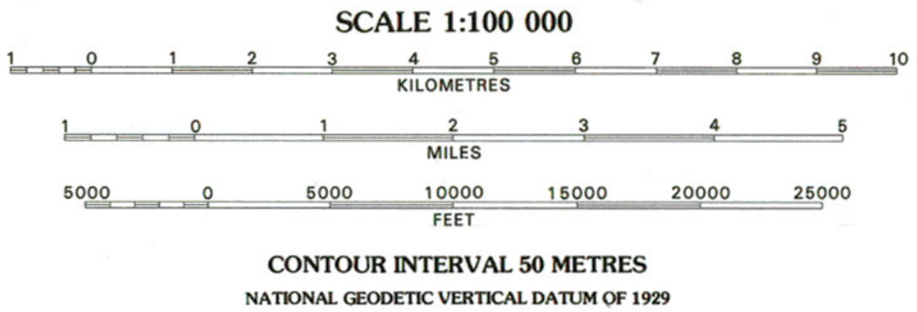


Figure 2.2: Scale bar on a map of 1:100 000. Courtesy of USGS.

The concept of LoD is closely related to the concept of scale and it was pioneered by Clark (1976). Nowadays it has various definitions depending on the usage, for instance:

- Luebke et al. (2003) state that LoD is used to improve the performance and quality of three-dimensional (3D) visualization in computer graphics. It follows a simple fundamental rationale: when 3D scene is rendered, it is optically sufficient and computationally efficient to use a less detailed representation for small, distant, or unimportant portions of the scene. Their definition is that LoD is "the real-time 3D computer graphics technique in which a complex object is represented at various resolutions and the most appropriate representation chosen in real time in order to create a tradeoff between image fidelity and frame rate. This term is often used interchangeably to refer to both the graphics technique and a single representation of an object."

- Fan & Meng (2012) and Meng & Forberg (2007) state that LoD is uniformly defined as a number of milestones along the scale space when taking the scale space of 3D buildings as a linear continuum. However, the researchers notice that there are no agreed LoDs for 3D buildings.

- The CityGML standard (Open Geospatial Consortium, 2012) denotes that LoDs are required to reflect independent data collection processes with differing application requirements. Further, LODs facilitate efficient visualisation and data analysis.

- The most concise definition was found on a Virtual Reality Modeling Language (VRML) tutorial website[1]: levels of detail specifies the set of alternative representations of a graphical object. In VRML a representation is selected depending on the distance from the object to the observer.

- Wikipedia notes[2]:

  > In computer graphics, accounting for level of detail involves decreasing the complexity of a 3D object representation as it moves away from the viewer or according other metrics such as object importance, eye-space speed or position. Level of detail techniques increases the efficiency of rendering by decreasing the workload on graphics pipeline stages, usually vertex transformations. The reduced visual quality of the model is often unnoticed because of the small effect on object appearance when distant or moving fast.

The presented list is just a selection of a series of definitions and explanations found in literature. While the derived definitions come from different backgrounds, they share the basic idea of having different levels of representation of data for computational and user aspects.

Scale and LoD are in literature sometimes interchangeable terms, this is not strictly correct. Loosely discussing, an LoD is sometimes a product of a generalisation algorithm which

[1] `http://www.lighthouse3d.com/vrml/tutorial/index.shtml?lod` (content accessed on 10 December 2012)
[2] `http://en.wikipedia.org/wiki/Level_of_detail` (content accessed on 22 November 2012)

is created through automatic methods from a *finer* LoD, while in some disciplines it is a representation of an object which is separately modelled, stored and queried.

In cartography, each scale can be seen as a level of detail almost equivalently as in 3D city modelling, however, this term is rarely used. In traditional cartography, each map is a LoD with a scale. Another map with either a larger or a smaller scale imply its own LoD. In digital maps with a more refined range of scales, the same LoD can be shared by more than one scale. In theory, while it is rare in practice, there can be combinations of using a *low* LoD in a large-scale representation, e. g. a 10K map with a representation which is more *suitable* for a 50K map.

On the other hand, scale is rarely used as a term in 3D city modelling. The literature in 3D city modelling seldom offers a definition what the Level of Detail (LoD) is, and there is no widely accepted definition.

This makes room for defining it in the frame of our research, and as another research subquestion.

At this proposal stage of the research, LoD will be used as a both a concept (topic) in general, and when dealing with discrete levels of detail also as a specific level of detail (e. g. LoD3), and it will not be dissected further into the definition of a level and of a detail.

The scale will be used similar as in cartography, but with caution. The scale is more applicable to materialised representations such as printed maps and physical 3D models which size of the representation can easily be related to the real-world.

2.3 Level of detail in computer graphics

The book *Level of detail for 3D graphics* by Luebke et al. (2003) provides a well-known introduction to the concept of LoD in computer graphics, and this section presents the summary of the book.

In computer graphics, geometric datasets can be too complex to render at interactive rates, therefore the solution is to simplify the polygonal geometry of small and distant objects. This theory is beside being known as Level of Detail (LoD), is also known as polygonal simplification, geometric simplification, mesh reduction, decimation, and multi-resolution modelling.

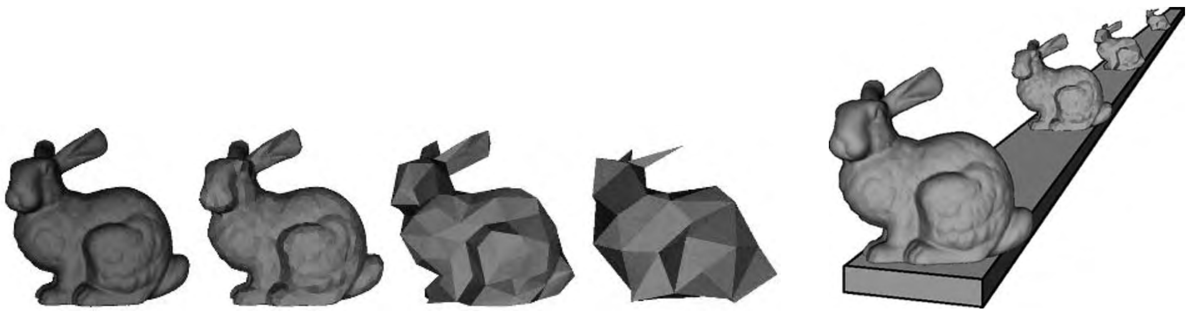
The LoD approach in computer graphics is mainly concentrated on the fidelity/performance trade-off, with the main task of how to represent and generate simpler versions of a complex model. The key words used in this discipline are *generating* and *rendering*.

The Figure 2.3, adopted from (Luebke & Hallen, 2001), shows the fundamental concept of LoD. A complex object is simplified (Fig 2.3a), creating LoDs to reduce the rendering cost of small, distant, or unimportant geometry (Fig 2.3b).

Research on LoD in computer graphics evaluates the fidelity of the simplified models, when to use which level of an object.

LoD can be divided into the categories:

- discrete LoD,



(a) (b)

Figure 2.3: An example of the LoD paradigm in computer graphics: representation and generation of simpler versions of a complex model.

- continuous LoD, and
- view-dependent LoD.

The first approach is traditional: create a fixed number of LoDs for each object separately in a preprocess, and at run-time, pick each object's LoD according to the object's distance or similar criterion. The LoDs are created offline at fixed distances, hence the name discrete LoD. This approach has the advantages that it is simple – decouples simplification and rendering, and it does not have to address real-time rendering constraints. Run-time rendering needs only to choose LoDs. The disadvantage is that it is not suited for drastic simplification where large objects must be subdivided and small objects must be combined (e. g. massive Computer-Aided Design (CAD) models) due to the popping effect (the noticeable flicker that can occur when the graphics system switches between different levels of detail.

The continuous LoD approach provides an advantage over the discrete LoD that creates a data structure from which a desired level of detail can be extracted at run time. It provides better fidelity (LoD is specified exactly, not chosen from a few pre-created options), and smoother transitions (continuous LoD can adjust detail gradually and incrementally, reducing visual pops).

In the end, the continuous LoD leads to view-dependent LoD which uses current view parameters to select best representation for the current view. Single objects may thus span several levels of detail. For instance, nearby portions of an object can be shown at higher resolution than distant portions. Such approach provides even better granularity (allocates polygons where they are most needed, within as well as among objects), and enables drastic simplification of very large objects.

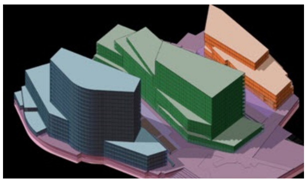
This approach is analogous to mixed-scale and perspective-view terms used in cartography and 3D city modelling (*cf.* van Oosterom & Meijers, 2011).

2.4 Level of development in building information modelling

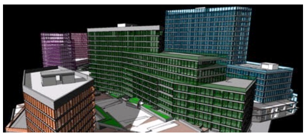
LoD in the frame of Building Information Modelling is the shorthand for Level of Development, a term related to this research.

In the definition used by the The American Institute of Architects (2008) there are 5 basic levels of development which do not reflect specific modelling guidelines for any particular software, rather a generic definition of model content and, more importantly, authorised uses of the model for the respective LoD (Figure 2.4):

- LoD 100 - Essentially the equivalent of conceptual design, the model would consist of overall building massing and the downstream users are authorised to perform whole building types of analysis (volume, building orientation, cost per square foot, etc.) (Fig. 2.4a)
- LoD 200 - Similar to schematic design or design development, the model would consist of "generalised systems or assemblies with approximate quantities, size, shape, location and orientation." Authorised uses would include "analysis of selected systems by application of generalised performance criteria." (Fig. 2.4b)
- LoD 300 - Model elements are suitable for the generation of traditional construction documents and shop drawings. As such, analysis and simulation is authorised for detailed elements and systems. (Fig. 2.4c)
- LoD 400 - This level of development is considered to be suitable for fabrication and assembly. The Model Element Author (MEA) for this LOD is most likely to be the trade contractor or fabricator as it is usually outside the scope of the architect's or engineer's services or would constitute severe risk exposure if such parties are not adequately insured. (Fig. 2.4d)
- LoD 500 - The final level of development represents the project as it has been constructed - the as-built conditions. The model is suitable for maintenance and operations of the facility. (Fig. 2.4e)

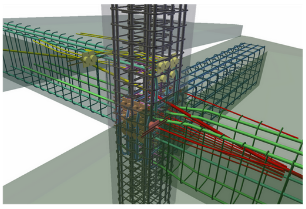


(a) LoD100.



(b) LoD200.

(c) LoD300.



(d) LoD400.

(e) LoD500.

Figure 2.4: Examples of levels of development in Building Information Modelling. Images courtesy of Mortenson Construction.

2.5 Level of detail in 3D city models

This subsection gives an overview of a few prominent views on the concept of level of detail in 3D city modelling, which is the focus of this research. Each example is described with its official definition if available, and a critical overview is given. In the end, all standards are compared and an analysis of the presented paradigms is given.

2.5.1 Comparison between known industry standards

CityGML

CityGML is a common information model and XML-based encoding for the representation, storage, and exchange of digital 3D city and landscape models. CityGML provides a standard model and mechanism for describing 3D objects with respect to their geometry, topology, semantics and appearance, and defines five different levels of detail. Included are also generalisation hierarchies between thematic classes, aggregations, relations between objects, and spatial properties. CityGML is highly scalable (extensible with respect to a theme) through CityGML Application Domain Extensions (ADE), and datasets can include different urban entities supporting the general trend toward modelling not only individual buildings but also wider sites, districts, cities, regions, and countries.

The CityGML standard (Open Geospatial Consortium, 2012) defines five LoDs, and its excerpt on this topic is listed below. An example of a house represented in CityGML with different LoDs is shown in Fig. 2.5.

> CityGML supports different Levels of Detail (LOD). LODs are required to reflect independent data collection processes with differing application requirements. Further, LODs facilitate efficient visualisation and data analysis. In a CityGML dataset, the same object may be represented in different LOD simultaneously, enabling the analysis and visualisation of the same object with regard to different degrees of resolution. Furthermore, two CityGML data sets containing the same object in different LOD may be combined and integrated. However, it will be within the responsibility of the user or application to make sure objects in different LODs refer to the same real-world object.

Further the standard defines:

- The coarsest level LOD0 is essentially a 2.5D Digital Terrain Model (DTM) over which an aerial image or a map may be draped. Buildings may be represented in LOD0 by footprint and/or roof edge polygons (2D shape in 3D space). If a building is represented by both its footprint and the roof edge polygon, the polygons are stored separately, which means that models in LOD0 do no contain volume and are not 3D objects.

  LOD0 is used for regional and landscape applications.

- LOD1 is the well-known blocks model comprising prismatic buildings with flat roof structures. This level is used for city and region coverage.

- In contrast, a building in LOD2 has differentiated roof structures and thematically differentiated boundary surfaces. LOD2 is most suitable for city districts and projects.

- LOD3 denotes architectural models with detailed wall and roof structures potentially including doors and windows. It is mostly used for landmarks.

- LOD4 completes a LOD3 model by adding interior structures for buildings. For example, buildings in LOD4 are composed of rooms, interior doors, stairs, and furniture.

- In all LoDs textures can be mapped onto the structures.

Therefore, practically the relation between LoDs could be seen in the following manner:

$$\xrightarrow{\text{footprint}} 0 \xrightarrow{\text{block model}} 1 \xrightarrow{\text{coarse exterior}} 2 \xrightarrow{\text{fine exterior}} 3 \xrightarrow{\text{interior}} 4$$

A few observations can be derived from the above definitions, the standard, and practical usage of CityGML data:

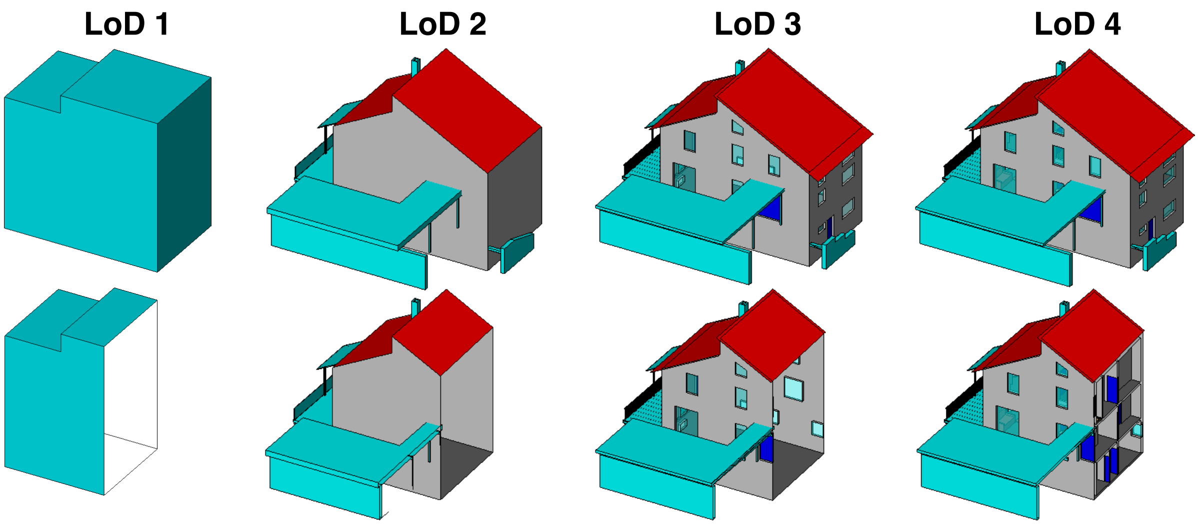


Figure 2.5: Four LoDs of CityGML. LOD0 is not shown here. Courtesy of Karlsruhe Institute of Technology.

- It can be argued that the LoD0 cannot be considered as a 3D city model since it is a boundary representation in 2D with a height as an attribute.
- Neglecting minor improvements in the exterior, LoD3 is basically in most of the cases an LoD2 with openings (e. g. windows and doors).
- LoD4 is an LoD3 upgraded with interior. The external geometry and the semantics remain equal.
- CityGML enables the simultaneous use of multiple representations in different LoDs, meaning that the concept of LoD is object-related, and not scene directed.
- There is not an explicit link between corresponding LoDs instances of different levels. For instance, in LoD3 when adding windows to a wall, the definition of the wall cannot be re-used from the LoD2. A single CityGML file can contain multiple LoDs, but their information is often duplicated. The relationship between LoDs is weak.
- The abstraction levels for features other than buildings are not clearly defined.

Furthermore, as other researchers observe:

- CityGML does not indicate methods for the automatic derivation of the different LoDs, and relationships between different LoDs are not maintained (Fan & Meng, 2012).

BLOM

BLOM is a Geomatics company from Norway. BLOM3D™ is the product name of its archive 3D models, which detail more than 20 million buildings in 340 urban models. The BLOM3D™ models have four different LoDs, ranging from simple wire frames to fully textured models. The product and LoD are described in BLOM's white paper (Blom ASA, 2011).

The descriptions of LoDs are listed for an overview:

1. Block Model (BlomLOD1™) contains 3D buildings each represented as parallelogram blocks, without the information on roofs or additional structures. The model includes a single colour for each block based on the predominant colour of the original building taken from the aerial imagery. (Fig. 2.6a.)

2. RoofTop (BlomLOD2™) contains 3D buildings represented as parallelogram blocks, with added roof structure and other constructions present on the building. As the previous LoD, this model includes a single colour in the blocks. (Fig. 2.6b.)

3. Library Texture Model (BlomLOD3™) is the RoofTop model to which library textures have been added to blocks. These textures are an approximation of reality and they are selected based on a similar colour and configuration of the real textures. (Fig. 2.6c.)

4. LOD 4 (BlomLOD4™) is the RoofTop model in which the building textures are extracted from oblique aerial images. (Fig. 2.6d.)

Thus, the geometry of the building has actually two LoDs (LoD1, while LoD2, LoD3, and LoD4 share the same geometry). The difference between the last three LoDs is in the texture: no texture, texture from a library, and (*actual*) photorealistic texture.

NAVTEQ

NAVTEQ is an American company that provides geo-information data for navigational products, and since they are suited for a specific application they are different from the datasets and standards presented so far.

Their products relevant to this research are (NAVTEQ, 2011):

- 3D city models, that enable applications to highlight specific buildings from search results and enable consumers to more easily orient themselves in unfamiliar or complex situations. They include untextured polygons outlining the footprint of a building, with basic rooftop shape and a height attribute defining the height of the building. It is unknown are the vertical polygons generated on-the-fly from the height of the building, or are included in the model as well.

(a) BlomLOD1™

(b) BlomLOD2™

(c) BlomLOD3™

(d) BlomLOD4™

Figure 2.6: Example of different LoDs in the BLOM3D™ product. Images courtesy of BLOM ASA, and adapted from Blom ASA (2011).

- Enhanced 3D City Models, whose improvement over the above product is that they contain texture, and it has a realistic representation of roads, and textured land use. Enhanced 3D City Models improve consumer guidance experience by making relevant buildings more realistic.

- 3D Landmarks, are photorealistic models of prominent landmarks such as a monument, building or other structure. 3D Landmarks can improve user orientation and sense of place in unfamiliar or complex situations.

The first two products have one LoD, however, loosely, they can be seen as one product with two LoDs distinguished only by texture.

Landmarks have a finer geometry, and photorealistic textures. Each structure is delivered in two LoDs, which are distinguished by their varying polygon count.

1. Light resolution: up to 500 polygons (faces). The average is 200.

2. Standard resolution: up to 1000 polygons. The average is 500.

There is not a clear boundary between these levels, since one object in light resolution can contain more polygons than another object in a standard resolution.

Additionally, each structure is delivered as an icon available for smaller applications in 64 x 64 pixels, but this cannot be considered as an LoD in the frame of our research.

The Figure 2.7 shows an example of a combination of the products Enhanced 3D City Model, and 3D Landmarks, in Munich. This is essentially a city model with a different combination of LoDs: the buildings have textures from a generic library, while landmarks such as churches have a finer geometry and a texture derived from photographs of the actual object.

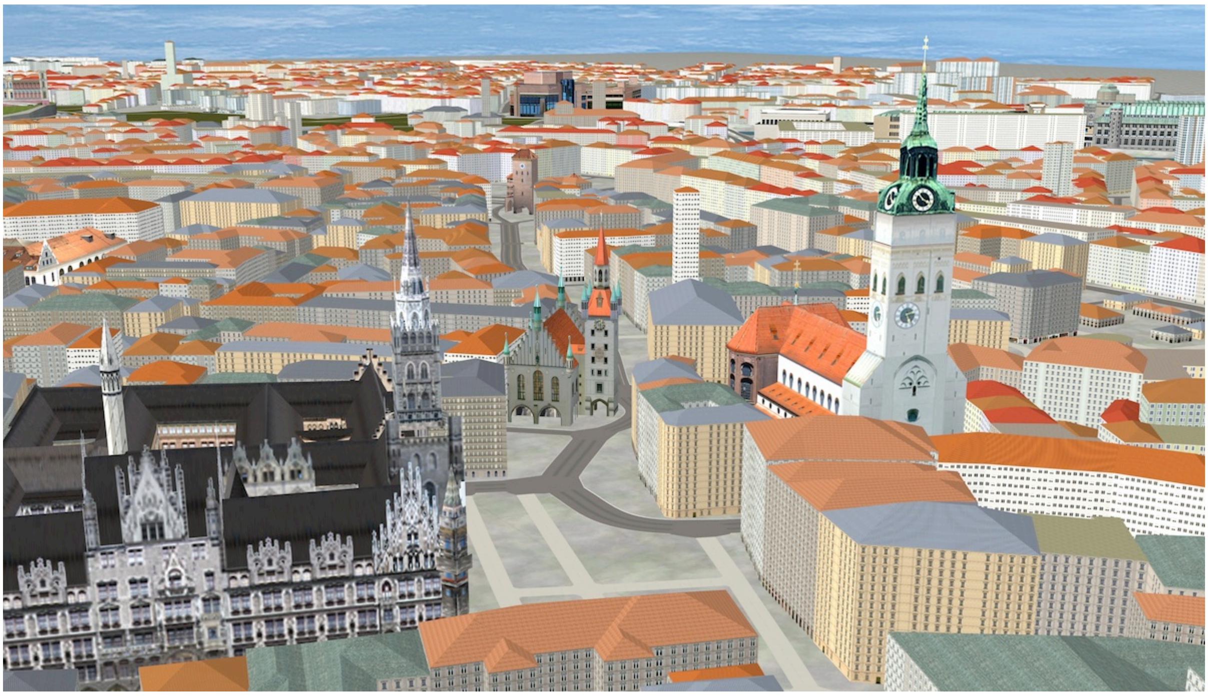


Figure 2.7: Mixed-LoD 3D city model of Munich by NAVTEQ as a combination of the Enhanced 3D City Model, and 3D Landmarks. Courtesy of NAVTEQ.

Summing up the three products listed above, we can conclude that NAVTEQ offers four levels of detail for their 3D city modelling products. The difference to the previous paradigms is that not every LoD is applicable to every structure in the model. Landmarks are never represented in a low LoD, while buildings and other *regular* objects are never represented by photorealistic textures or fine geometry as landmarks.

2.5.2 Analysis and observations

The mutual motivation for having a series of LoDs in 3D city modelling is:

- Removing clutter in visualisation
- Computational reasons
- Using no more details than it is actually required
- Economical aspects

This section gives the analysis of the given (discrete) LoDs in 3D city modelling according to different variables. Table 2.1 shows an overview of the presented views. LoDs in the presented examples are all *driven* by the exterior details. There are two more factors to denote: texture and interior. CityGML supports textures, however, this is not LoD dependant.

Table 2.1: Comparison between different levels of detail paradigms presented in the §2.5.1.

Example	No. of LoD	Exterior-driven	Texture-driven	Interior-driven
CityGML	1+4	Yes	No	Yes
BLOM	4	Yes	Yes	No
NAVTEQ	4	Yes	Yes	No

LoD designation Regarding the nomenclature, the presented LoDs paradigms have in common that the discrete levels are on an ordinal scale, and not on a ratio scale, e. g. the LoD2 does not contain a double amount of details of the LoD1. This is expected, as it would be hard to quantify the level of detail in such paradigms. In general, that means that there is no quantitative measure of the amount of details.

Further, in terms of the amount of details (whether exterior, texture or interior) LoDs are always a monotonic increasing function that always increases as the amount of detail increases, i. e. LoD(n)>LoD(n-1) for all n.

Application or context The most important observation is that the LoD paradigms presented in §2.5.1 show that in 3D city modelling there is not an uniform approach to what defines an LoD, and what *drives* their definition. The levels are generated according to a specification, and are used regardless of the application or the context, e. g. they are equal whether the 3D city model is used for estimating the solar potential or for urbanism applications, or if they have a specific application they are used only for one application.

Accuracy and precision The accuracy of geometric data is not taken into account. It is unclear is a fine model, but acquired with less precise acquisition methods, still considered as a fine LoD.

Generation of lower levels of detail It is not clear how are levels of detail lower than the finest LoD generated. Two possible methods are generalisation and separate modelling of each LoD.

Elements of an LoD The interrelation between the levels in all paradigms is of interest to note as well. We observe that the three most prominent variables in the presented LoD approaches are:

- Exterior geometry, or simply: exterior
- Interior geometry, or furniture (not correct, but common)
- External texture, or simply: texture

Their relation and inclusion (position) varies between the presented concepts. By isolating each variable above, we can observe that the LoDs are made of the combination of LoDs concerning each variable. We can define these as Sub-Level of Detail (SLoD). Two examples are given: CityGML and Blom3D, and backed up with the Figure 2.8.

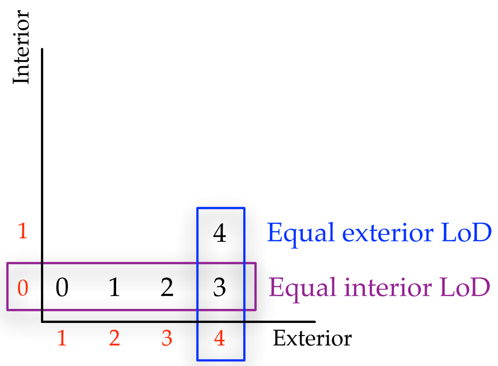
CityGML (Fig. 2.8a) has five LoDs. The LoDs from LoD0 until LoD3 are distinguished with the number and quality of details in the exterior geometry, i. e. there is a progressive increase in exterior detail. The highest LoD, LoD4, is basically an LoD3 with added interior, meaning that LoD3 and LoD4 share the same abstraction level with respect to the exterior. Considering the interior, all LoDs except the LoD4 share the same level of detail of the interior – i. e. none.

Therefore, the LoDs of CityGML can be subdivided into multiple SLoDs:

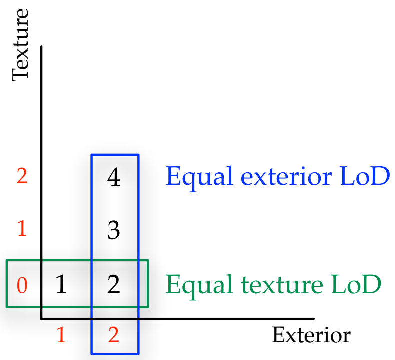
- Four SLoDs for the exterior: 1 (LoD0), 2 (LoD1), 3 (LoD2), and 3 (LoD3, and LoD4).
- Two SLoDs for the interior: 0 (LoD0, LoD1, LoD2, LoD3), and 1 (LoD4).

Notice that the first SLoD in case of the exterior is 1, while the first SLoD for the interior variable is 0. This is because the first SLoD for the interior does not contain any detail, which is contrary to the CityGML definition where the LoD0 is not "empty".

A similar logic could be applied in the case for Blom3D, but in this case with the texture instead of the interior. The Blom's approach has 4 LoDs, however, the last three share the same exterior geometry, meaning that in such case there are only two distinctive LoDs representing the exterior. The last three levels (LoD2, LoD3, LoD4) are distinguished by the detail of their texture. In such a case the approach is first exterior-driven, and then texture-driven.



(a) Decomposition of CityGML LoDs to sub-LoDs.



(b) Decomposition of Blom3D LoDs to sub-LoDs.

Figure 2.8: Viewing LoDs as a composition of multiple SLoDs. Example of CityGML and Blom3D.

It is important to note that in all the presented paradigms, the amount and quality of details are either increasing or staying the same with the level of detail, regardless of the variable involved. This might seem obvious, but there is not any mixing of different SLoDs, like having a coarse exterior and fine interior.

Another observation that we can make, is that the SLoDs never progress together. In the CityGML case, first the details of the exterior increase, and the whole. The details of the exterior and the interior do not progress together with respect to the LoDs.

Such thought is shown in the Figure 2.9 for the case of BLOM. The first two LoDs see the increase of the exterior detail without any texture involved, while the texture progresses only after the last exterior level has been “finished”. Afterwards, there is no improvement in the detail with respect to the exterior. The red dots denote the LoDs.

When considering the three NAVTEQ products as one, similar analyses can be made, but with different results. This is shown in Figure 2.10. The NAVTEQ buildings which are not of special interest (regular objects) are stored in two LoDs which have the same exterior detail but are distinguished by texture (Fig. 2.10a). The landmarks have both a finer exterior and texture, and their SLoDs progress together. It is clear that the LoDs for regular objects and landmarks are separated (Fig. 2.10b), however, this is interesting to note as their products' visualisations include a mixture of different LoDs, and that the LoDs never overlap for the two different classes of structures.

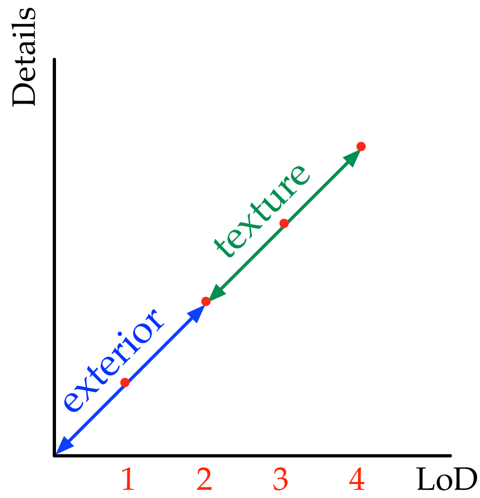
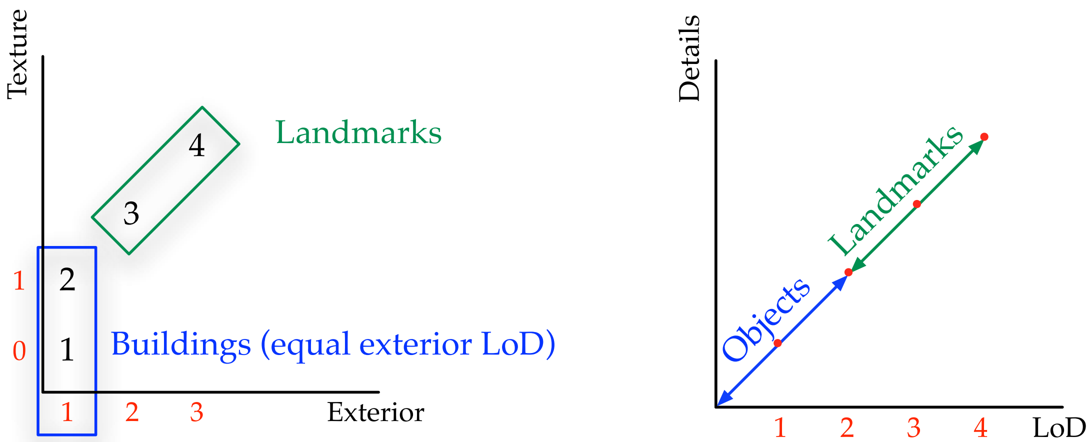


Figure 2.9: The two details (exterior and texture) of the LoD paradigm of Blom progress separately. It is similar as CityGML if considering the interior instead of the texture.



(a) Decomposition of NAVTEQ LoDs to sub-LoDs.

(b) Progress of details of texture and geometry in the NAVTEQ LoDs.

Figure 2.10: Analysing the four levels of details of the three NAVTEQ 3D products.

2.5.3 Relation to computer graphics

When comparing the LoD paradigms in 3D city modelling to the ones in computer graphics, two differences can be observed:

1. Regardless of the application and discipline, in 3D city modelling it is possible to divide the LoD purpose in two categories, but not in computer graphics:

    - Use of LoD for visualisation purposes.

This is primarily the topic of computer graphics, where *excess* details of a model are removed in order to make the computational aspects of the visualisation more efficient. This is the principal purpose of LoD in computer graphics.

- Use of LoD for analysis and computational purposes.

  Beside visualisation purposes, in 3D city modelling there are applications which are focused on analysis (e. g. noise modelling). The advantage of using different LoDs 'behind the curtains' is to make computations faster.

In 3D city modelling, there is an overlap between the two categories by using the same LoDs (there are no separate LoDs for visualisation and for computational purposes).

2. Apart from the creation of the finest LoD, the creation of lower LoDs in 3D city modelling is not discussed in literature as much as in computer graphics. There are two general ways of creating *lower* LoDs:

   - With generalisation, i. e. automatically reducing meaningful content, an approach standard in computer graphics.
   - Separate modelling, i. e. manual and semi-automatic acquisition/modelling of each level of detail.

   Further, it is not discussed is there a possibility to automatically create an intermediary LoD in between two different LoDs, e. g. if CityGML LoD1 and LoD3 are separately acquired and available, is it possible to automatically generate an LoD2 from both datasets (levels).

2.6 Vario-scale geo-information

The vario-scale data structures are related to this research. The following works describe the concept of vario-scale and the smooth tGAP structure (Meijers, 2011; Meijers et al., 2012; Meijers & van Oosterom, 2011; van Oosterom & Meijers, 2011, 2012a,b), while this section gives the key conclusions which can be used for this research.

The researchers introduce the concept of the smooth tGAP structure represented by a space-scale partition (a 3D space-scale cube) in which the scale is integrated as a spatial dimension, i. e. map generalization of 2D polygonal regions is seen as extrusion into the third dimension (Vermeij et al., 2003). The most detailed data is stored once, and an incremental object by object generalisation process is run and represented in a data structure.

The most concise description of the space-scale 3D cube is found in paragraph in a paper by Meijers & van Oosterom (2011): "The space-scale cube permits us to obtain an integrated 3D model, composed of both the dimensions of 2D space and 1D scale (or level of detail). From the 3D cube it is possible to extract a consistent 2D map at variable scale (as the cube is one integrated model of space and scale any derived slice from the cube must again be a valid 2D planar partition).”

Latest papers, such as (Meijers et al., 2012), discuss of the extension of the approach one dimension higher, i. e. for 3D city models: “A vario-scale approach for 3D models would offer the possibility to continuously zoom-in and out across levels of detail, without jumping to another discrete representation (as in CityGML), because the LODs are integrated in the 4D data structure itself. In addition it allows the continuous representation of a city model, i.e. not restricted to the arbitrary five fixed LODs (in the case of CityGML). Slicing the 4D data cube permits us to obtain a 3D city model at any given LOD.”

Their approach constitutes a strong foundation for this research, and this research will directly relate to the Vario-scale Geo-information project.

Chapter 3

Proposed PhD research

After the analysis of the state of the art (Chapter 2), and considering the 5D project of which this research is a part, this Chapter proposes the methodology of this research *The concept of level of detail in 3D city models*, and across multiple sections provides the following aspects:

- General direction, scope of the research, research topics, and goals with the motivation (§3.1)
- Section 3.1 also describes the separation of the research in themes and phases with a connection to research questions given in §1.2.
- Initial concepts of the methodology are given in §3.2-§3.5
- Justification of the research (advantages), in §3.6

It is composed in a step-by-step style divided in themes. Practical aspects as timetable and stakeholders are given in the next Chapter.

3.1 Shortcomings of the current paradigms and motivation

Chapter 2 gives the overview of the concepts of scale and Level of Detail (LoD) in various disciplines, primarily 3D city modelling. The key shortcomings of the LoD paradigm in 3D city modelling are listed:

- It is not unambiguous what an LoD is in 3D city modelling.
- There is not a single and widely-accepted LoD paradigm in 3D city modelling. Outside specific standards such as the OGC/CityGML, there are no general guidelines, and it is not clear what drives the LoD.

- The number of LoDs in the presented standards is limited (discrete).
- There is no LoD concept which adapts based on the application.
- LoDs of the same object are frequently acquired, modelled and stored separately. There are obvious computational challenges with current LoD approaches, primarily redundancy.
- LoDs are not integrated in a single data model or entity, which potentially leads to inconsistency.
- Accuracy and precision requirements are not addressed for a certain level of detail.
- Mixed-scale/perspective-view in 3D city modelling is not researched.

Further, the following have not been investigated throughly:

- tGAP and vario-scale extension to 4D for 3D geometry + scale

The aim of this research is to provide a theoretical foundation to overcome the above disadvantages. In order to achieve that, this research is divided in the following parts (themes) and linked to the research questions presented on page 2, and the described will be investigated:

1. Definition of LoD: what is level of detail from our perspective. This theme will answer the research questions 1–3.
2. Hyper-cube integration: how to integrate the scale and 3D space in a single entity as the fourth spatial dimension. Research questions 4–7 will be answered through this part of the research.
3. Context awareness: how to create a level of detail suited up exclusively for an application or context. Formalising this theme will answer the research question no. 8.
4. Generate customised LoDs: how to generate a continuous or discrete number of levels of detail from the space-scale hypercube taking into account the context, and is it possible to create mixed-scale views. The last part of the research will answer the remaining research questions 9–11.

To the extent of my knowledge, the proposed points have not been yet throughly investigated. It is expected that this research is novel in all of the above stated points.

The presented themes are not strictly sequential and do partially overlap. A finer scope and content will further evolve through the research.

The next four sections provide the overview of each part with its themes. Each theme has a motivation, task, deliverable, and initial concept (methodology).

3.2 Definition of a level of detail paradigm

3.2.1 Background

Contemporary definition I see the current approaches for the construction of LoDs as a 1:1 mapping relation where each level of detail is acquired, stored, maintained and queried separately.

$$O_1, O_2, \ldots O_n \to l_1, l_2, \ldots l_n \tag{3.1}$$

where O_i denotes an abstraction level in the modelling process of an object, and l_i the resulting level of detail.

The current paradigms do not take into account the applications for which the models are used, hence the mapping process is static.

A concept of our definition This section gives a direction of a formal definition of LoD, and its initial concept. An object O in theory has an infinite number of representations (levels), depending on a set of different criteria or factors.

$$O \to l_1, l_2, \ldots l_n \tag{3.2}$$

which can be seen as a 1:n mapping relation in the modelling process.

An LoD can be seen as the result of a function considering into account an index i (level of abstraction)

$$l_i = f(O, i) \tag{3.3}$$

where the index is composed of a number of different criteria based on the context.

$$i = [C_1, C_2, \ldots C_n] \tag{3.4}$$

The variables C_i are defined as a set of parameters depending on the context of a use-case of the city model, e. g. application, computational aspects, field of view, distance to the observer. This approach makes the generation of LoD *context-aware*.

This can be clarified through a graphical example. Figure 3.1 shows the standard LoD paradigm, there is a discrete number of level of detail, regardless of the context.

The finest level of detail (n) contains all of the available details, regardless of the application. The generation (or modelling) of lower levels ($0 \leq i < n$) depends on the context. Here there are listed three examples of contexts and functions: a general one, a context where window features are important, and a third where the application demands that the roof structure should be preserved even in the low levels of detail. Therefore, the context *drives* the rules for generation of levels of detail. This approach is dynamic comparing to the classic LoD approach which can be considered as static.

This view takes into account the following rules:

Figure 3.1: Classic (static) LoD approach from the finest to the coarsest level of detail, e. g. LoD4, LoD3, LoD2, and LoD1.

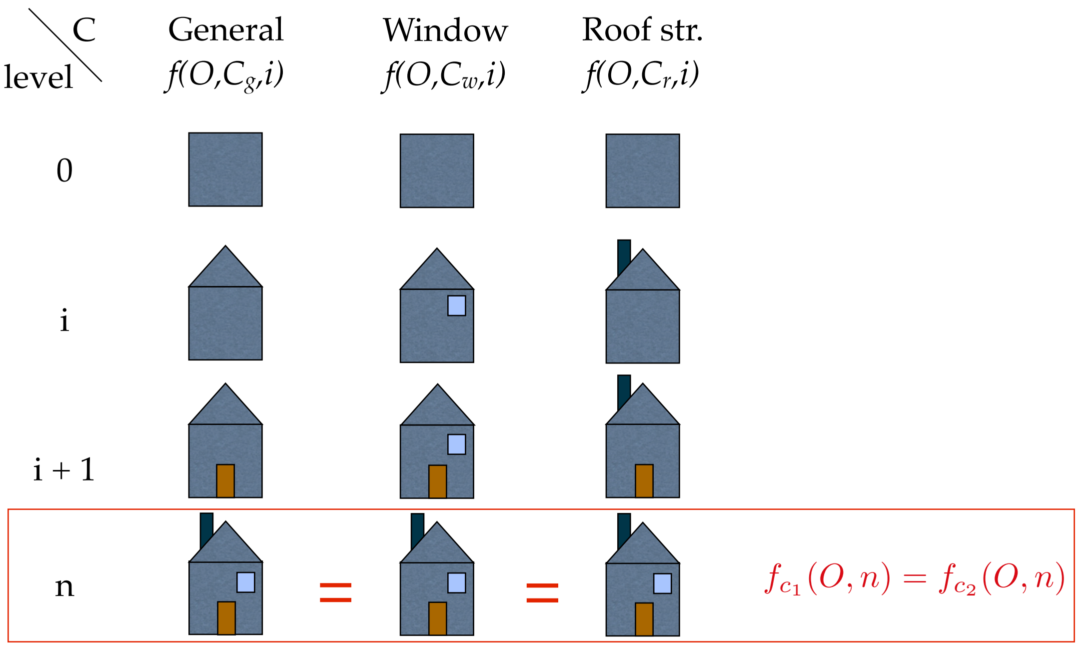


Figure 3.2: Context-aware and dynamic LoD approach.

1 $l_{i-1} \leq l_i$
(The amount of detail in each step (level) is smaller or equal than the higher level)

2 $l_0 \leq l_i \leq l_{i_{max}} \forall i \in [0, n]$
(Each level is always in between the coarsest and finest LoD)

3 $l_{i_{max}} = f(O, i_{max})$
(The highest index (level) is equal to the finest LoD available regardless of the context)

We can describe our view in set theory as well. Each level is a subset of the next level.

$$\{a \in l_{i-1}\} \subseteq \{a \in l_i\} \subseteq \{a \in l_{i+1}\} \tag{3.5}$$

Introducing generalisation and other concepts makes this definition not exact. For instance, two adjacent buildings in one LoD could be generalised into one object in a lower LoD. In such case the higher LoD does not contain such object. However, we consider the above definition valid in a semantic-oriented GIS view.

3.2.2 A formal definition of level of detail

The main deliverable of this part of the research is a broad literature review, end user requirements, and a new definition of LoD both in the GIS and mathematical term which will serve as a foundation for the next steps in the research. The previous subsection gives a short overview of what the definition could include.

The key research tasks and topics are:

1. Investigate current industry standards and the general theory and application of 3D city models.

   This has already been covered for the most part in the previous chapter. In order to complete this section to the full extent, a few visits or contact with institutions through questionnaires, primarily with companies and government agencies, are possible.

2. Find related concepts in cartography

   Cartography deals with scales and generalisation of 2D data, in two manners: fixed-scale and vario-scale approach. While it is related to 2D data, many concepts could be borrowed.

3. Investigate acquisition and modelling techniques.

   In order to get the full overview on the 3D city modelling industry and workflows, visits to relevant institutions are suggested. These can be integrated with visits described in the previous point.

   Some examples of information which will be gathered:

   - Does the acquisition company have their own standard for LoD?
   - Does the LoD paradigm vary between clients and projects?
   - What type of data is present in all levels of detail?
   - What is the accuracy and precision of the geometric data and is there a requirement for a certain LoD?

4. Selection of use-cases. Research the industry needs through questionnaires.

   In order to apply the methodology, and investigate various needs. The list of proposed use-cases is given in the previous chapter. The findings of use cases will also be applicable in the forthcoming phases of the research.

   The use-cases should be diverse, but in line with the possibilities of the research (e. g. institutions which already had a collaboration with TU Delft).

   This will be realised with questionnaires and direct contact. An example of the questions which will be included in the questionnaires:

   - How many LoDs are used in your task?
   - Which LoD is used for what purpose?
   - What are the most important features in your application?
   - What are the metric (i. e. accuracy, precision) expectations per each level of detail?
   - What are the topological requirements per LoD, or view-dependent LoD?

   The selection criteria for institutions are that they are diverse (public institutions between local and state level, and private companies), and domestic institutions. Foreign institutions can be contacted without visits.

5. Define the LoD in the frame of 3D city modelling and GIS.

   The key task of this part of the research, and one of the research questions (no. 3), is to produce our own definition of what an LoD in the frame of 3D city modelling and GIS is. The definition will be composed of a theoretical, mathematical, and linguistic view, and in Unified Modelling Language (UML).

   For instance:

   - Can we define the LoD with a set theory, or as a mathematical function?
   - What is a level, and what is a detail? What is the wealth/amount/quality of detail?
   - What means a finer and what means a coarser LoD?
   - How to denote the progressiveness of higher LoD in a mathematical way? E. g. how to denote that in CityGML LoD2 is finer than LoD1, and contains more details?
   - What are the differences in between the singular and plural of LoD, e. g. level of detail vs. levels of detail? What about capital letters, is it level of detail or Level of Detail?
   - Can we separate the use of LoD in different meanings, e. g. LoD as a single level (LoD2) vs. LoD as a paradigm? How?

- Can we define a theory which is valid for both a discrete and continuous LoD approach?

This will be limited to 3D city modelling, and not computer graphics or cartography.

6. Separation of Levels of detail into sub-levels and components.

   As discussed earlier in the second chapter, each LoD is composed or sub-levels and components. This research will decompose 3D city models into components which are meaningful for a specific context, or in general.

7. Make a clear distinction between LoD, scale, and possibly granularity.

   This is already slightly described in introduction of this proposal. The separation between these terms is not yet strictly defined in the term of 3D city modelling, which gives room to being a research question.

8. Quantification and possible metrification of the LoD.

   From a relative view, with current ordinal scaled LoD approaches, it is not possible to define to put the levels in an interval or ratio scale, e. g. that LoD2 has twice the amount of detail than LoD1.

   Analysing absolutely but also relatively, currently it is also not possible to quantify the amount of details, e. g. what means when a level has 60 % of the detail.

   A measure could be defined, such as the number of points in the model.

   This task will aim to solve the above issues, and further: define the range and units with which a level of detail can be expressed.

   For instance, should LoDs be expressed in a range between 0 and 1. What is the content of LoD0? Does LoD1 present the fullest available level of detail, or LoD1 exist only for reality. Is there a linear relation between the levels? Are there units which should be used to express a level? Is the range supporting continuous LoDs?

9. Formal expression of LoD valid content in UML.

3.3 Representation of levels of detail as a spatial dimension

3.3.1 Background

In line with the 5D project, of which this research is an integral part, the integration of LoD (or scale) as a spatial dimension will be investigated.

The integration of LoDs in a separate and stand-alone spatial dimension is not unknown in GIS (vario-scale, see the work of Meijers (2011)).

3.3.2 Theoretical foundation and motivation

Basically, the goal of this part of the research can also be seen as the extension of the variable scale approach to one dimension higher. This part will investigate is it possible to integrate scale as a spatial dimension in 3D city modelling, i. e. as the 4th dimension.

3.3.3 Methodology

1. Investigate the applicability of a 4D model, and development of a hyper-dimensional foundation.

   This part will consist of the research of hyper-dimensional theories and their applicability to this research.

   Some of the theories that will be developed are:

   - Representation of different objects in 4D space
   - Applicability of the hyper-cube/tesseract in storing the space-scale object
   - Slicing the space-scale object and 3D hyper-plane slicing of the 4D hyperspace (see Section 3.5)

   A parallel to the vario-scale approach will be made.

2. Creating the 3D+Scale hypercube.

   The first step of the integration is the creation of the 3D+Scale hypercube where the (discrete) series of 3D LoDs are stored in hyperspace and linked. There are two options in this approach:

   a) Existing 3D object matching in which corresponding objects in subsequent LoDs are found and linked, e. g. CityGML LoD1, LoD2 and LoD3.
   b) Generation of LoDs from the finest available through generalisation

   In order to understand the integration of scale as the fourth spatial dimension, the Figure 3.3 shows an example: a simple cube-like house with a door in a pseudo-4D view. Two levels of detail are stored: a finer one (blue), and a coarser (black), where the door in both levels (green) has a different level of detail. The two levels are *linked* through a fourth spatial dimension (red), via the so-called trans-scale boundary of the 4D object (described by van Oosterom & Meijers, 2012b).

   Other related tasks will also be researched, e. g. definition of a minimum bounding box in 4D, topological relations, and applicable data formats.

   This part of the research will investigate alternative implementations if this one will prove impractical or not possible.

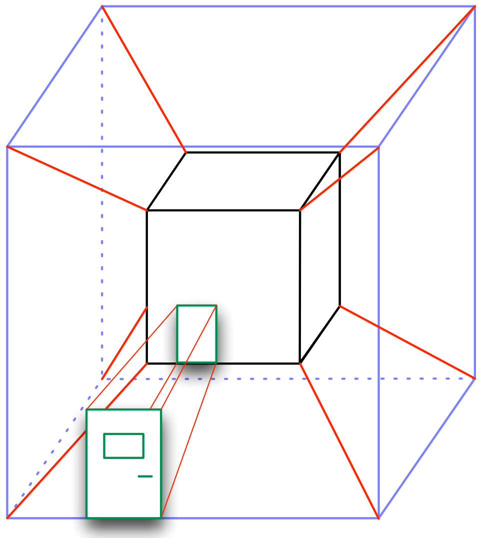


Figure 3.3: Storing two levels of detail in a 4D tesseract-like object.

3. Implementation of the quantification (and metrification) of LoDs.

   The Figure 3.3 does not address the metrification of the fourth axis. Since the LoDs are integrated as a spatial dimension, they should be placed on a spatial axis, hence the dimensions should be discussed as well. Each LoD should be placed in its *place* on the *scale axis*. This mostly depends on the last step of the previous theme *Quantification and possible metrification of the LoD* (see §3.2.2).

   Conclusions from that task will be used in this step.

4. Maintaining the relationships between features through a hierarchy of rules.

   Another key task is to link the relationships between features (details). The discussed example shows two LoDs in hyperspace, however, they could also be seen as *floating* in hyper-space, as they are not fully linked, i. e. each detail is not connected between different levels.

   This can be achieved through a hierarchy of rules where each feature is separately linked with another.

   Another challenge is to connect the features through hyperspace. In the same example, the door in the finer level has details which are not present in the door in the coarser level. It will be researched how to connect features and details which do not exist in one of the levels.

   This task will be started practically with linking existing LoDs in sample data, for instance, CityGML LoD1 and LoD2.

5. Automatic generation of supplementary levels of detail.

   The above relationships will require the generation of supplementary levels of detail, i. e. auxiliary projections in hyperspace. For instance, a chimney collapsing from a cube to a line might not be linked without creation of a supplementary level of detail between existing LoDs, i. e. shape of the trans-scale boundary.

6. Slicing the 4D hypercube with a 4D surface of required LoD

   This part will research the theoretical possibilities of slicing the space-scale 4D hypercube for generating the required LoD.

7. Optional: Integration of texture and interior.

   The last part will investigate how to integrate the texture and the interior in the developed methodology.

   If these will require development of additional concepts, this part will be abandoned.

3.4 Context awareness

3.4.1 Background

The current LoD paradigms do not take into account several factors on which the LoD depend. We call this context, and it can be considered as one of the pillars of this research.

The view of this research is that each application requires different features in different detail, and having a uniform LoD paradigm in that sense leads to redundancy (some of the features are not needed) and on the other hand also loss of the information (some of the features should be detailed even in the coarsest LoDs).

For instance, in estimating the solar potential of roofs, *non-roof* details such as windows on walls and doors are not relevant and can be omitted in all levels.

3.4.2 Methodology

1. Constitution of a context and the factors.

   This task will investigate the prominent factors which constitute the context in the frame of this research.

   For instance, the context may be composed of: perspective view, area, distance to the observer, computational aspects, application needs, available data, and the neighbourhood of the 3D city model(s). An example of a context is visualisation of noise modelling data of a city centre of size of 5 km (at once).

2. Investigation of use cases and quantification.

Taking into account application needs and developing rules is the focus of this research. A general theory will be developed, and requirements of a series of applications will be investigated through a selection of use-cases. One or two use use cases will be selected from the list given in §2.1.2.

This will be achieved through practical work with software, and visits to institutions (connected with the surveys in the first theme). For each use-case the importance of each feature or component will be discussed and quantified.

This part of the research will answer questions as:

- How many levels are required for each context?
- Which features have less priority than others?
- Can we group (aggregate) certain details?
- What is the required accuracy for a certain level of detail in an application?

Following the example of noise modelling, the research will investigate what are the minimal requirements for such context: e. g. two discrete LoDs, aggregation of smaller residential buildings, no textures and no interior, and no openings on walls.

3. Effects of the usage of different LoDs

   Computation-wise, different LoDs yield different results in most of the applications. For example, using a CityGML LoD1 in calculating the shadow effect will in many cases have different results than using LoD2. This is shown in Figure 3.4. A house in LoD1 is shown in dark grey, while LoD2 brings the roof structure (light grey). Sun rays are depicted with dashed lines. The boundary sun ray for LoD1 is in red, and the ground shadow is shown in red as well. The case for LoD2 is shown in green respectively. The ground shadow calculation is different for the two LoDs.

   This theme will therefore investigate the effects of using different LoDs through the defined use-cases.

3.5 Generation of levels of detail from the space-scale 4D hyper-cube

The final theme will deal with the generation of levels of detail from a 4D hypercube taking into account the context in order to generate customised levels of detail suited for an application.

1. General (horizontal) slicing or scale-stamping.

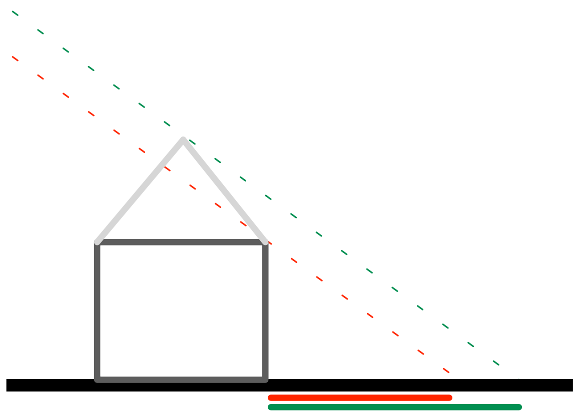


Figure 3.4: Different levels may produce different results in computations. This example shows that the shadow calculation for the same building in two different LoDs, namely CityGML's LoD1 and LoD2, yields different results.

This task will deal with the construction of a foundation for (horizontal) hyper-slicing in order to generate new levels of detail and their visualisation. This is related to the task 6 in §3.3.

As an example, Figure 3.5 shows a pseudo-4D view where scale is integrated as a 4th dimension, and the generation of a new level of detail is done through slicing the hyperspace with a hyper-plane.

A fine LoD – LoD_1, and a coarse one – LoD_0 are linked together in a 4D data structure. The intermediary LoD_x where $0 \leq x \leq 1$ is generated with slicing the datastructure.

2. An additional topic which may be investigated in this frame is *non-horizontal* slicing as an analogy to a view-dependent LoD approach found in computer graphics and vario-scale (perspective-view).

3. Integration of rules in slicing for a context-aware generation of levels of detail.

   Beside general slicing, in order to generate the customised LoD, the context should be taken into account.

   The context awareness can be expressed through weights, where each detail is given importance.

   This part might involve building individual space-scale hypercubes per each context.

4. Assessment of continuous levels of detail.

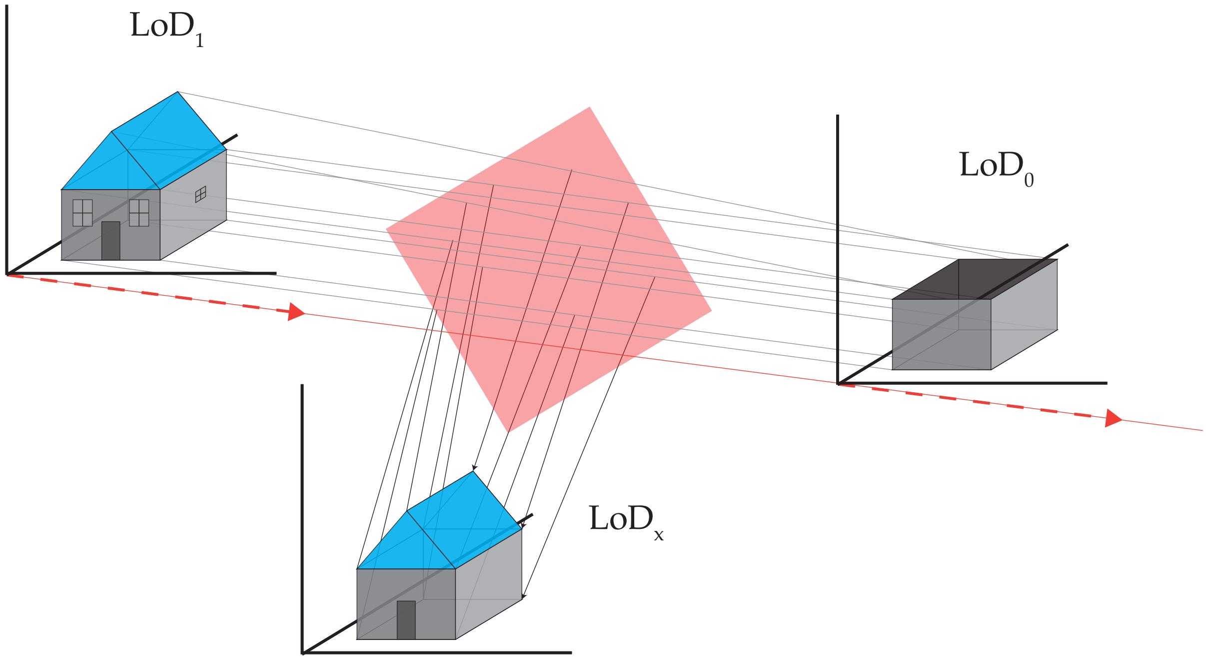


Figure 3.5: Conceptual view of *slicing* a new intermediary level of detail between a finer and coarser level in 4D.

Continuous levels of detail will be investigated as well. If this fails, then discrete levels will be generated, and more emphasis will be given to the research of their required number which will be investigated according to each use-case.

3.6 Contribution and benefit of the research

3.6.1 General and GIS benefits

- A new refined and formal definition of LoD
- Basis for an international standard
- Creation of context-aware levels of detail
- Storage of all levels in a single data model and 4D hyper-cube
- Stronger link between multiple LoDs (inter-linking), and trans-scale boundaries

3.6.2 Computational benefits

- Storage of less levels of detail
- More effective querying
- Removal of redundancy and inconsistencies
- Support of progressive transfer

3.6.3 Economic and business benefits

- Acquisition and maintenance of just one representation.
- Scalability of a dataset for different applications, and data representation focused for one application
- Availability of a finer set of LoDs (*intermediate scales*)
- Mixed-scale (perspective-view) LoDs

Chapter 4

Planning and practical aspects

This chapter outlines the plan and practical aspects of the research presented in the previous chapter, through a timetable (§4.1), short-term plan (§4.2), assessment of risks (§4.3), list of stakeholders and supervisors (§4.4), proposed software and data (§4.5), research visits out of the university (§4.6), and employment aspects (§4.7). The skills required for this project are listed in §4.8.

This project will have several deliverables presented in §4.9, with the list of journals and conferences given in §4.10. Graduate school aspects are described in §4.11.

4.1 Timetable

This research will be conducted over a period of 48 months, and it is divided in sequential phases:

0. proposal,
1. research,
2. formalisation, and
3. conclusion,

as shown in the Table 4.1 in more details with tasks and activities for each phase. The research started in July 2012, and all time frames presented below are relative to that time.

The four research themes presented in §3.1 (p. 27) are not strictly sequential, and will be investigated with a high degree of overlap in time, hence they will not be further divided into phases. The estimated conclusion of the research is in July 2016 following a PhD thesis submission and defence.

Table 4.1: Phases of the research and their duration

Phase	Title	Duration	Tasks and Activities	Key deliverable
0	Proposal	6 months	Literature review Defining research questions Defining research scope Planning and organisation	Proposal
1	Research	24 months	Broad literature review Definition of use-cases Creation of the 4D cube Investigate the 4D integration and 3D LoD object matching Development of an LoD theory Early testing and experiments	Prototype
2	Formalisation	12 months	Formalise the research Work on visualisations	Concept
3	Conclusion	6 months	Writing the dissertation Preparing the defence	Dissertation
Total		48 months		PhD Degree

This plan is subject to change according to the flow of the research. Detailed plans for each phase will be made before and during each phase, e. g. the plan for the Phase 0, which is presented in §4.2.

Several tasks and activities will be a part of all phases:

- Publication of research in journals and on events.
- Attendance of conferences, workshops, and other events of importance.
- Extended and continuous literature review in order to keep it up-to-date.
- Education, including summer schools, courses, and self-study.
- Research visits, contacts with partners, progress tracking, and reporting to supervisors.

- Outlook and update of the research plan.

4.2 Short term first-year plan with milestones

This section presents the proposed key events and milestones in the first 12 months of research listed in Table 4.2.

The first year beside the writing, submission and acceptance of this proposal, will include attending four events and writing a two general papers about the research. The date for the Go/No Go meeting will be planned for after 8 months of the start of research, i. e. during March 2013.

In end of June 2013, after a year of research, a progress meeting with the supervisors will be organised.

Table 4.2: Key events in the first 12 months of the research

Month	Key event
2012-07	Start of the research
2012-08	
2012-09	
2012-10	Attend 3U3D conference
2012-11	Present at the GIN symposium
2012-12	Submission of the draft of the proposal
2013-01	Attend Workshop CityGML in national mapping
	Present at a section (lunch) seminar (qualifier)
	Submit a short paper for AGILE 2013
2013-02	Final acceptance and publishing of the proposal
	Continuation of the literature review
2013-03	Research use-cases
	First experiments and practical work
	Go/No Go meeting with external professor
2013-04	Writing a full paper for 3D Geoinfo 2013
	or for the ICA/EuroSDR Generalisation Workshop
2013-05	Present at AGILE 2013
2013-06	Reflection on the first year of research

4.3 Risks

There is a number of risks in this research. This section describes possible bottlenecks and barriers which have to be taken into account.

- Validation of 4D data generated in this research.

  Currently there are not methods to validate 4D data (3D+Scale) that will be developed through this research.

  This can be mitigated through the development of our own basic validation algorithms.

- New field with lack of literature and young concepts.

  The spatial integration of time, scale and other *attributes*, which earlier have not been seen as spatial dimensions is new and under development. While an nD foundation is fairly described and defined, some of the concepts may not be yet developed to fully support this research.

- Failure of creation of the 4D hypercube.

  One of the central topics of this research is to create a 4D hyper-cube with sound relationships.

  While the vario-scale project shows that scale can be integrated with 2D geometry (i. e. maps), it is reasonable to be aware of the possibility that the same may not be possible for 3D models.

  In case of failure, this will be mitigated with alternative theories and approaches which will be investigated, e. g. a 4D approach which is not *smooth*, created through extrusion of 3D objects to 4D.

- Failure of generation of LoDs with slicing the 4D hypercube.

  Generation of new LoDs through hyperspace slicing is also one of the central issues of this research. However, this may not be possible to the full extent.

- Failure of generation of continuous levels of detail.

  In case that generating continuous levels of detail will prove unfeasible the research will be concentrated on a discrete number of levels according to each use-case.

- Performance issues

  The developed theories may be computationally too expensive to implement. In that case, the research will use lighter datasets.

4.4 Involved parties

This section contains the list of people and institutions which take part in this research.

4.4.1 Dutch Technology Foundation (STW)

The research is a part of the project 5D Data Modelling: Full Integration of 2D/3D Space, Time and Scale Dimensions, which is funded by the Dutch Technology Foundation STW, a part of the Netherlands Organisation for Scientific Research (NWO) and partly funded by the Ministry of Economic Affairs, Agriculture and Innovation. (Project code: 11300)

4.4.2 Supervisors

This research will be supervised by

- Dr. Jantien Stoter, Associate Professor at the Section GIS Technology
- Dr. Hugo Ledoux, Assistant Professor at the Section GIS Technology

The supervisors will guide me in the research on a daily and weekly basis. As a rule, regular (progress) meetings with the supervisors will be held weekly. The change of this schedule depends on the stage and challenges of the research.

For every meeting, an agenda will be prepared, and notes will be taken. On every second meeting the progress according to the research plan will be discussed.

4.4.3 Promotor

The PhD research will be promoted by Prof. dr. Peter van Oosterom, Chair of Section GIS Technology. Meetings with the promotor will be sporadic and related to milestones, e. g. proposal submission and before major conferences. The promotor's tasks and responsibilities are given in the Article 8 of the TU Delft Doctoral Regulations.

4.4.4 Partner institutions

It is proposed to have a list of domestic and foreign institutions which are related to 3D city modelling. Since this thesis will include a series of use-cases, and will investigate many practical aspects of 3D city modelling, it is expected to have contact and/or visit institutions which are relevant to 3D city modelling in any aspect.

The number of such parties is not defined, and the list will vary during the research based on the direction of research and progress. There is already a number of parties related to the section, or involved in the 5D project, such as the user commitee: Rijkswaterstaat, Bentley, Gemeente Rotterdam, Kadaster, Gemeente Den Haag, 1Spatial, Gemeente Amsterdam, Oracle, ESRI, and TomTom. Further, there are many parties involved in the 3D Pilot NL in which our section participates.

Examples of institutions include:

- Aalborg University
- C3 technologies/Apple
- Cyclomedia
- European Institute for Energy Research
- Fugro
- Google
- Hansa Luftbild
- IGN France
- Karlsruhe Institute of Technology
- M.O.S.S. Computer Grafik
- Graduate school of architecture of Nantes
- Port of Rotterdam
- TeleAtlas
- TU Berlin
- TU Eindhoven
- TU Munich
- Witteveen+Bos
- Wuhan University

4.4.5 Advisors and support staff

During the stages of the research, it is expected to have several persons, in or outside the university as advisors for a specific field. At this point there are certain needs as:

- During the research, especially in its early phase, it is expected to have more intensive contact with John Zhao, visiting researcher at TU Delft specialised in 3D generalisation, Ken Arroyo Ohori, PhD researcher on the same project, and other PhD researchers of the section involved in other projects.
- Mathematician, for the multi-dimensional foundation.
- Linguist, for the formalisation of linguistic aspects of the definition of LoD.
- Questionnaire expert, for improving the quality of surveys. This is already provided by the OTB Research Institute.

These matters, incl. other potential parties, will be defined further through the research.

4.4.6 Contact

The contact with the above mentioned parties will be established as shown in Table 4.3.

Table 4.3: Contact with parties involved in research.

Frequency	Person	Topic and goal/result
Daily	H. Ledoux	Daily assistance and guidance
Weekly	J. Stoter, H. Ledoux	Progress tracking
	J. Zhao, K. Arroyo Ohori	Consult during a specific task and stage
Monthly	5D+vario-scale team	Project meetings
Twice a year	P. van Oosterom	Longterm tracking of progress and consulting
	STW user committee	User committee meeting
Sporadic	Support staff	Contact during a specific task
	Institutions	Research on use-cases and end-user requirements
	Others	

4.5 Tools and technical aspects

This research will be implemented to a partial or full extent, based on the complexity and scope of the results of the theoretical work. The The main programming language of this research is Python, while it may include others such as C++. Visualisation tools include Paraview, and FZK Viewer. The selection preference of the software will be given to open-source solutions. Commercial software will be used as well, such as the packages from ESRI and 1Spatial.

Sample data (3D city models with fixed LoDs) will be obtained from partners (§4.4.4). The preferred format is CityGML, but other formats such as Collada, VRML, and KML will be taken into account as well (Stoter et al., 2011; van den Brink et al., 2013).

The publications and other documentation will be typeset in LaTeX.

4.6 Research visits

This research will require visits to institutions of relevance to the project.

Short visits (e. g. one-day) will be made to partners (§4.4.4) for analysis and discussions, e. g. visiting the Municipality of the Hague to survey the usage of 3D city models for estimating the solar potential of roofs.

It is expected to have at least one longer visit to a university or company. This will be defined later depending on the progress of the research.

4.7 Employment

The employment is carried out through TU Delft through a standard 38-hour appointment (FTE 1.0), and it is regulated by the contract and employment regulations of TU Delft.

Yearly employment requirements are stated in the Result and Development Cycle for staff member of the TU Delft (R&O). It was already agreed that in the first year 80% of the working time should be devoted to research and its publication. Subsequent years will be defined in its respective R&O agreements and cycles with the supervisors.

The guideline is that a minimum 75% of working time shall be devoted to research and its publication. The rest of the working time will be assigned to other activities which are preferably related to the research topic (e. g. supervision of an MSc thesis related to 3D city modelling, or teaching activities in 3D city modelling MSc courses).

The progress of work will be tracked through meetings with supervisors and presentations (project meetings, lunch seminars), and in the frame of the R&O cycle.

4.8 Required skills

The presented research requires the following skills:

- Programming
- UML modelling
- 3D city modelling
- CityGML and other standards
- Mathematics and geometry
- Scientific and soft skills skills (e. g. writing scientific publications, presentation on conferences)

The researcher already possesses most of the skills, and they will be developed further through the following channels:

- Self-study, especially in programming, and UML modelling
- Practical work, especially regarding the modelling and application of 3D city models
- MSc courses, such as the data visualisation course offered by the Faculty of Electrical Engineering, Mathematics and Computer Science

- Workshops and conferences during the whole duration of the PhD. In the first year events such as the EuroSDR/OGC Workshop in national mapping, and the COST action on the usage, usability, and utility of 3D city models, will be visited.

- Courses at research schools, or summer schools, such as the yearly ISPRS summer schools

- Discipline related PhD courses, organised by the Faculty of Architecture and OTB Research Institute

- Discussion with other researchers

- Research visits, such as Wuhan University, or the Technical University Munich

The next priority is to familiarise with 3D city modelling, and especially the CityGML standard. This will be done through January and February 2013 with practical work and consult with colleagues.

Soft skills are not listed in details, but they are further developed through the compulsory Graduate School education which is spread over the whole 48 month research period (see §4.11).

4.9 Deliverables

This section presents the main deliverables that will be published during and after the research:

- This proposal, as a literature review, and agreement of the research.

- Journal papers. The list of potential journals is given in §4.10.1. Some (extended) parts of this proposal may be submitted for publishing in the next year. It is expected to have a published journal paper for each theme of the research.

- A PhD thesis. The main document as the final report of this research with the findings, formalised concepts, and answers to research questions.

- Presentations and papers on conferences, workshops, and symposia.

- Datasets, source code (published open-source), and examples.

- MSc thesis topics. During the research, a number of MSc thesis topics will be defined which can accompany and support this research.

4.10 Journals and conferences

This section lists the relevant journals and conferences in this discipline that will be considered when publishing findings.

4.10.1 Journals

This section contains the list of journals that will be considered when publishing:

- ACM Transactions on Graphics (TOG)
- Cartographic Journal
- Cartography and Geographic Information Science (CaGIS)
- Computational Geometry: Theory and Applications
- Computer-Aided Design (CAD)
- Computers & Graphics (CG)
- Computers & Geosciences
- Computers, Environment and Urban Systems
- Discrete & Computational Geometry (DCG)
- Environment and Planning B
- Geoinformatica
- IEEE Computer Graphics and Applications (CG&A)
- International Journal of Applied Earth Observation and Geoinformation
- International Journal of Computational Geometry and Applications (IJCGA)
- International Journal of Foundations of Computer Science (IJFCS)
- International Journal of Geographical Information Science (IJGIS)
- International Journal of Spatial Data Infrastructures Research (IJSDIR)
- ISPRS Journal of Photogrammetry and Remote Sensing (ISPRS)
- Journal of Geographical Systems
- Journal of Land Use Science (JLUS)
- Journal of Location Based Services (TLBS)
- Journal of photogrammetry, remote sensing and geoinformation processing (PFG)
- Journal of Spatial Science (TJSS)
- Marine Geodesy (UMGD)
- The Professional Geographer (PG)
- Transactions in GIS (TG)
- Annals of GIS
- International Journal of 3-D Information Modeling (IJ3DIM)
- International Journal of E-Planning Research (IJEPR)
- ISPRS International Journal of Geo-Information (IJGI)

- Journal of Digital Earth (TJDE)
- Journal of Spatial Information Science (JOSIS)
- Journal on Data Semantics
- Geo-spatial Information Science
- Cartographica: The International Journal for Geographic Information and Geovisualization
- Photogrammetrie, Fernerkundung, Geoinformation

This list will be updated based on the direction of research, impact factors, and other relevant events during the research.

4.10.2 Conferences and symposia

This section contains the list of workshops, symposia, conferences that will be considered for attendance or publishing, but it is not limited to:

- 3U3D2012: Usage, Usability, and Utility of 3D City models (COST action)
- International Workshop on Geoinformation Advances
- Geo-informatie Nederland
- Urban Data Management Society
- Geospatial World Forum
- AGILE Conference on Geographic Information Science
- 3DGeoInfo conference
- International Conference on 3D Web Technology
- Workshops of the ICA Commission on Generalisation and Multiple Representation

This list will be updated periodically.

4.11 Graduate School and regulations

This PhD should be followed through the enrolment in the Graduate school of the University, and according to the Doctorate Regulations of the Board for Doctorates of TU Delft. A minimum amount of 45 graduate school points should be collected, which is done through courses and practical activities.

With the enrolment in September 2012, I became a part of the Architecture and Built Environment (A+BE) Graduate School of TU Delft. The following courses on the University Graduate School will be taken

Year 2012/2013

C9.M1 PhD Start-Up (3 c.)

C7.M1 Teaching and Active Learning (1 c.)

C7.M2 Assessment of Learning Results (1 c.)

C8.M5 How-to: Become a Confident and Effective Networker (1 c.)

Year 2013/2014

C1.M1 Problem-solving & Decision-making in research (1 c.)

C8.M3 Self-management Strategies (2 c.)

C8.M4 Achieving your goals and performing more successfully (3 c.)

C13.M5 Writing a Scientific Article in English (3 c.)

Year 2014/2015

C11.M10 Build a better brain (1 c.)

C13.M1 Presenting scientific research (3 c.)

Year 2015/2016

C5.M2 Writing a Dissertation (3 c.)

C10.M1 Career Development workshop (1 c.)

In addition to the Graduate School courses, additional courses that are relevant to this research and in accordance to the duties presented in the employment contract and R&O will be taken:

- Nederlands voor buitenlanders 1 (Volksuniversiteit Delft)

The list of courses is subject to change. The Graduate School revises the list of courses yearly. The above listed courses are worth 25 Graduate School credits.

The rest of the credits will be collected through Learning-on-the-job activities, and it is distributed through the four years (also see §4.8). Its valuation will be assessed by the Graduate School and the list includes but it is not limited to:

- A paper review
- A poster presentation
- Writing a research proposal
- Supervising of a Bachelor student group
- Teaching assistance

- Writing the first journal article
- Writing the first conference paper
- Addressing a major international audience
- Participating in an organisation (e. g. PromooD, PhD council)

These activities will be achieved and regulated through the R&O, research plan, and in agreement with the supervisors. At least 20 points have to be collected in through these activities.

The Board for Doctorates of TU Delft published the *Doctorate Regulations* (first published in 2004, amended in 2012) with rules for the PhD progress. This research will comply to the regulations.

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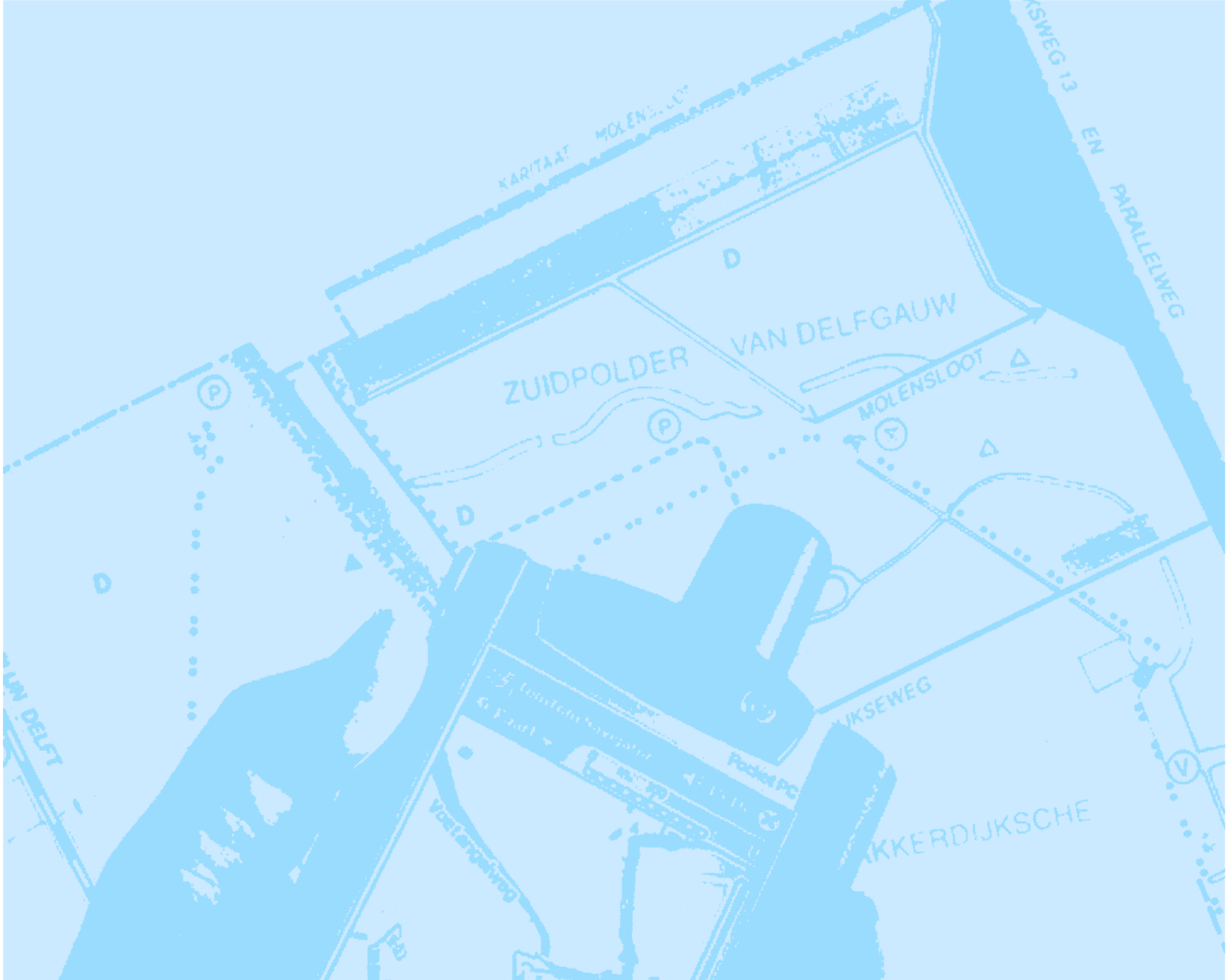
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