1 Why do we need vario-scale maps?

Maps have always played a significant role in history. They have helped sailors on their Pacific journeys, they have provided information to generals for planning invasions, and they have been used for more pragmatic reasons, such as tax collecting. Nowadays, maps are even more important because they are part of many fields and easily accessible in every smartphone; however, their form differs. While maps on paper still exist, most of them are transferred via the Internet, where users could in principle use the full potential of interactive computer environment, *e.g.* zooming. Nevertheless, with respect to their creation, retrieval and visualization, maps have stayed more or less the same as in the past. Therefore, this thesis focuses on map creation processed more suitable for interactive computer environment.

In the next section (Section 1.1), the main issues of the current solution are introduced. Section 1.2 suggests an advantages of the researched system. Main research questions covered in this thesis follow in Section 1.3. Furthermore it highlights the research scope in Section 1.4, the research methodology in Section 1.5, and gives an overview of the thesis structure in Section 1.6.

§ 1.1 Paper maps in digital enviroment

One of the main limitations of the classical approach to map making is the concept of scale, similar to the concept of Level of Detail (LOD), where the scale of a map is defined as the ratio of a distance on the map to the corresponding distance in real world. When moving to a computer environment, the old map scale concept is maintained with redundant data and content overlaps between scales (with potential inconsistency).

Other consequences of the classical 'paper' approach is the redundancy of data. Every time, when a user zooms in or out, a new predefined separate map is retrieved. With many separate fixed levels, a lot of information is the same, but still needs to be included, *i.e.* the identical map features are depicted in the map again and their geometries are stored multiple times in the database. This leads to duplication, more data transfer and slower response, because the same data must be sent from the server to the user's device repeatedly.

Maintenance and updates of the data are also an issue. The same features at different levels lack any connections most of the time; for example the same lake at two different scales is represented by two different objects. Then, sometimes even the name must be independently updated, the multiple representations (scales) must be visited, checked and modified. Therefore, this lack of links between data at different scales results in more complex analysis, search or processing.

A final issue is related to user navigation. The interactive Internet environment offers smooth animated changes of the content, or gradual transition between feature representations; for example when a user zooms in towards the most detailed level, the geometry of the building gradually appears. These dynamic changes are the result of the continuous map approach. However, continuous generalization is not applied to maps presented on the Internet. There are already map user interfaces providing that feeling by simulating a smooth zoom, *e. g.* Google Maps[1], Mapbox[2] and Microsoft Bing Maps[3]. However, this is just an illusion. Their solution is still based on a large number of redundant and fixed map scale representations.

Together, these issues result in a labour intensive and expensive process in the manner of handing geo-informations at range of scales, which in practice results in different and sometimes conflicting versions of the same data appearing in different places, so-called inconsistencies. Therefore, a new approach for a digital environment is needed.

§ 1.2 Vario-scale

We use a concept named 'variable-scale' (vario-scale for short) proposed by van Oosterom et al. (2014), where the data once stored in a vario-scale data structure can be used for generating all desired (needed) scales in a smooth digital way. The main idea of our alternative approach is based on the specific vario-scale data structure called tGAP (topological Generalized Area Partition) (van Oosterom, 2005; van Oosterom and Meijers, 2011b). This structure actually represents the results of map generalization actions; features are generalized in small steps, progressively leading to a simpler and simpler map.

We assume that map objects can be well generalized with optimized algorithms with appropriate parameters for use at any map scale. Therefore, we make the whole map repeatedly simpler and simpler, where the least important feature in the map is simplified based on a global criterion. These generalization steps are stored in the vario-scale data structure, which captures these incremental changes with minimal redundancy. Both the detailed objects at the largest scale and the objects generated during the generalization process are represented in a set of database tables.

Redundant storage is avoided as much as possible; instead of the explicit geometrical representation for every face as polygon, it stores only the shared boundaries between neighbouring faces (edges in the topological sense) in the specific structure. Once the automated generalization process is finished, a valid range of map scales is defined for every topological primitive (node, edge or face) in the structure. These primitives including scale ranges can then be used to construct maps at arbitrary map scale.

All objects are stored as 2D objects in a topological data structure (tGAP) extended with scale ranges. Up to now, the data have been stored and visualized as 2D maps, but this did not result in true smooth zooming operation (sudden small changes in map

1 `www.maps.google.com`

2 `www.mapbox.com/gallery/`

3 `www.bing.com/maps`

content are visible during use as result of specific generalization action). Therefore, a 3D structure called Space-Scale Cube (SSC) (Meijers and van Oosterom, 2011) where objects are represented as 3D volumetric data (2D geometry + 1D scale) has been proposed. In this structure, these (small) steps are represented by gradual transitions. However, this theoretical concept has not yet been implemented prior to the start of this PhD research.

Vario-scale approach is ongoing research proposed in multiple publications. These studies have provided theoretical and technical background for the vario-scale concept in general. However, there are still a significant number of unproven suggestions for improvement. Therefore, further design and development with respect to vario-scale cartographic map content generation and use is the main goal of this thesis.

§ 1.3 Research questions

The vario-scale research has been carried out for some years already (within the TU Delft, GIS technology group) with some principles suggested and proven and many more not yet proven. The main question at this research is the following:

MAIN: *How to design and develop a system for vario-scale maps?*

This research question is valid for whole vario-scale research theme and it will be main question of this thesis. From here more specific sub-questions are defined connecting to previous research (Meijers, 2011). Therefore, the sub-questions we want to address are following (together with corresponding chapter within brackets):

SUB I: *How much is the current map generalization process automated?* (Chapter 2)

This will give us solid starting position for our research. It also shows state-of-the-art solutions of map generalization. Since the vario-scale concept is known for some time already it investigates if such research about automated generalization still has meaning. This knowledge is needed to drive the generalization process of which the result is stored in a vario-scale structure.

To provide the foundation for this thesis and to understand the whole vario-scale concept together with the reasoning behind, we need to answer:

SUB II: *What is the state of the art vario-scale map?* (Chapter 3)

The previous investigated structures only explicitly support area features and the content/cartographic quality was not optimal. Other features (line and point) are not yet included explicitly in the structure. However, these types of objects are important for maps. Some line features are already implicitly produced during the creation of the tGAP structure. The collapse of an area feature is a good example, *i. e.* the area of road is converted to a line. It is convenient to store information about the collapsed feature as well. Therefore, we are looking for an answer of the question:

SUB III: *How can we produce improved vario-scale data content?* (Chapter 4)

Often, the efficiency of early solution is bounded by the size of datasets. Since geographical data are typically massive, they do not fit in the main memory of computer. This is a challenging process in general, but especially true in cases, in which the relationships between (nearby) features in the map must be considered. Therefore, we pose the question:

SUB IV: *How can we create vario-scale data content not fitting in main memory?* (Chapter 5)

Our approach in theory could generate map content supporting smooth gradual changes in user map interaction when treating scale as third dimension and using the 3D geometries where smooth zooming in or out is thus equivalent to the vertical movement of a horizontal slice plane (downwards or upwards). However, there are no practical experiences or implementations prior to this PhD research yet for either creating nor using this 3D structure. Therefore, the last questions are:

SUB V: *How can we generate, use and validate vario-scale data to achieve a smoother impression by the user?* (Chapter 6)

The answers will give us a tool to verify theoretical concepts about usage of the 3D geometries for smooth zooming more practically. Further, to test whether vario-scale map is perceived better than multi-scale map we can raise the question:

SUB VI: *How do the users perform with vario-scale map compare to multi-scale map?* (Chapter 6)

To reach the better vario-scale maps these research questions should be answered. Furthermore, to make the thesis more readable, clear and structured, every specific question will be covered in one chapter (except the last two).

§ 1.4 Scope

The following list of topics, conditions or domains define the scope of the research:

- The whole research is carried out with vector data only (no raster nor point cloud data). 2D input data are considered.
- Detailed description is from 2D GIS development perspective mainly.
- Examples and test cases with real data are used to demonstrate and evaluate proposed vario-scale solutions.
- Development prioritizes Digital Landscape Model (DLM) containing spacial representation of objects from real world; in contrast to a model targeting production of maps (i. e. geometric representation of objects is adapted to the styling of the map), the so-called Digital Cartographic Models (DCM)(Stoter et al., 2010).

It is also important to say what is not in the scope of this thesis. The following is a list of topics that are in support of this research, but beyond its scope:

- Cartographic design of high quality paper maps (as the emphasis here is more on interactive map use).
- Cartographic map design for various representations between scales, as with increasing number of scales the map levels may present differences in terms of representation.
- The generic output of our work is 2D maps. This implies that 2D resulting maps are our main focus, 3D geometries of higher dimensions are used to support better 2D output.
- Integration with other data. Cases when a base map (in vario-scale) is combined with, for instance, a thematic foreground map are left out.
- Improving data transfer (including data compression) from the server to the end user.
- Dynamic structure. The current tGAP structure is a static one. However, changes of data over time and recomputing the structure on-the fly is out of scope.
- Text labels or symbols of Points of Interest (POI) are also an important part of map content, but these will not be considered in the research.
- Integration of the vario-scale approach within the framework of Open Geospatial Consortium (OGC) standardisation.

§ 1.5 Methodology

This thesis is part of the bigger ongoing line of generalization research towards supporting vario-scale maps. An example of a vario-scale data structure is the tGAP data structure proposed in (van Oosterom, 2005) and since then extensively investigated and further developed.

Various aspects were covered in the multiple earlier publications, including PhD thesis by Meijers (2011) and even registered as a patent (van Oosterom and Meijers, 2011a). Another important characteristic of the research from the early beginning till now has been international cooperation, *e. g.* , with Wuhan University, the University of Hanover or Universiti Teknologi Malaysia (also known as UTM) which leads to multiple publication such as (Ai and van Oosterom, 2002; Dilo et al., 2009; Huang et al., 2016) and provide important reflection from different perspective. Moreover, our research team is an active member of the Commission of Generalisation and Multiple Representation of International Cartographic Association (ICA) and participate in annual Generalisation and Multiple Representation workshops. These activities give the possibility to share our experience and receive important feedback from the experts in the field.

Last four years were funded by the Technology Foundation STW in the project called 'Vario-scale geoinformation' (project code 11185) and the vario-scale research objectives fitted within the definition of this project. The aim of the Technology Foundation STW is to realise knowledge transfer between technical sciences and users. To this end, STW brings researchers and (potential) users together. The instrument par excellence in this respect is the user committee which is also the primary valorization instrument. The user committee meets twice a year and gives feedback (reflection on the research results and suggestion for further direction of the research). The members of the committee are experts in the GIS field: Dutch Kadaster, Rijkswaterstaat (RWS), the municipalities of Amsterdam, Rotterdam and The Hague and Geo-ICT industry: Bentley System Europe B.V., ESRI Nederland B.V., 1Spatial Group Ltd. and Oracle. The committee meetings provide work frame for the project and it helps plan, design and validate the project in half a year time intervals.

In addition to this, we proceed in the iterative way similar to software development process described in (Tutorials Point, 2015); The process of development runs in cyclic manner repeating every development step after every cycle of the process, in so-called iterations. In our case it can be summarized as following: First the theory is developed, make a solution for small test data set, test a solution against real world data, validate, adjust theory and draw conclusions. Then, every following iteration, solution is improved, more features and modules are designed, coded, tested and added to the prototype. Every iteration produces a solution which is complete in itself and has more features and capabilities than that of the previous one. Our prototype is open source and it is shared via online repository. It can be found on following website:

`varioscale.bk.tudelft.nl`

The final result of the process is vario-scale map in tGAP structure. Therefore, it is also important to mention how the quality of the result is measured. Most of the time we define and use quality indicators which can be retrieved automatically from the process such as feature size, the number of objects per features class and area distributions etc. More subjective measures are also involved in the process; visual inspection of map quality, visual comparison with results of previous iteration, and usability testing to limited extend.

§ 1.6 Outline of the thesis

This thesis is organized in the structure which is depicted in the Figure 1.1. It reflects the specific content of individual chapters and relationships among them. They should be perceived as independent contributions and also as closely related (overlapping) components of the unique solution called vario-scale maps. We acknowledge the developing approach where created tools for specific aspect of the problem can be reused later in the process again.

Since map generalization is a rapidly developing field, Chapter 2 gives an overview of map generalization with a focus on automated and continuous map generalization. It introduces related work where maps without fixed target scales with smooth transition are produced. Additionally, it presents state-of-the-art technology for generalization on a national level, because National Mapping Agencies have made enormous improvements in automated generalization lately. These agencies provide solutions characterized by the size of the dataset (millions of records), but also by complexity of their solution (many map features together).

This will provide the base for Chapter 3 where the detailed description of our solution for automated continuous generalization is introduced, resulting in vario-scale maps. Chapter 3 covers the whole vario-scale concept including several (untested) suggestions for better vario-scale maps, recent developments and the process design of the

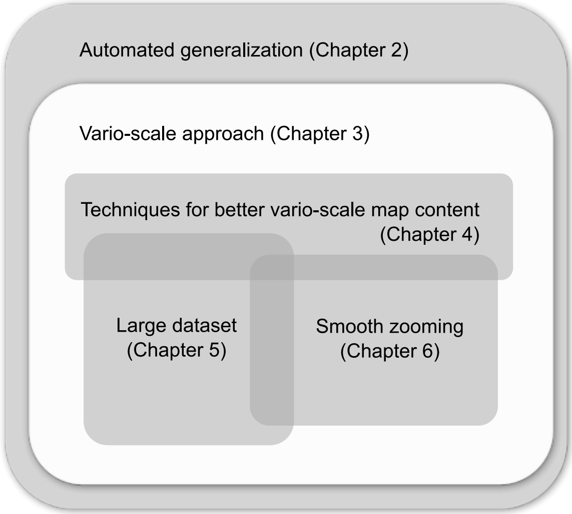

FIGURE 1.1 Outline of the thesis

generalization. It will specify vario-scale framework for the whole thesis where more specific issues will be addressed.

Therefore, one of the issue is to further design and develop the current techniques for better vario-scale map content, develop/find algorithms for the various suggested improvements, and assess the effect when applied to real data. Based on this deeper insight and enriched experiences; again provide/develop suggestion for further improvements. For example, the earlier solution did not consider the different data density of the map *i. e.* very dense urban area compare to sparsely populated rural region, or the fact that the vario-scale generalization process runs throughout whole scale ranges. Therefore, these limitations will be explored in Chapter 4 with specific attention to road map network. We will present developed process from large scale, where roads are represented as area objects, to mid and small scales, where roads are represented as line objects. This generalization of the road network throughout whole scale range is only one of the issues how to design, implement and enrich tools for better vario-scale content covered in Chapter 4.

Another aspect is handing real world dataset containing millions of records. If we want to create vario-scale structure of real world, we should know how to deal with such sizes. Therefore, special attention is paid to this in Chapter 5, where we choose a strategy of splitting the dataset in smaller parts. After that every part has to be computed separately and in the end these have to be merged together. This is repeated at several overlapping levels to avoid hard/remaining boundaries. Chapter 5 describes how to orchestrate such a process.

Later in the process of creating vario-scale maps, when users are involved, zooming in and out of a digital map, it is often necessary to modify the shape of the map. If this is done abruptly, it leads to big changes in geometry, perceived by the user as a 'jump' on the screen. Therefore, Chapter 6 to present smooth zooming operations to the user. This is based on the assumption that every 2D feature in the map is represented in 3D, where the 2D coordinates are the original representation, and the third dimension represents the scale value.

Chapter 7, finally, concludes all aspects, provides critical overview and reflection based on previous chapters, which can lead to further development of vario-scale concept with its promising potential, reduced redundancy, more functionality and better user perception than current classical fixed-scale (multi-scale) maps on the Internet.

Table 1.1 shows an overview of the publications on which the chapters in this thesis are based.

TABLE 1.1 Publications and their relation with the chapters of this thesis.

Ch.	Publication	No.
3	van Oosterom, P., Meijers, M., Stoter, J., and Šuba, R. (2014). *Abstracting Geographic Information in a Data Rich World: Methodologies and Applications of Map Generalisation*, volume 2014 of *Lecture Notes in Geoinformation and Cartography*, chapter Data Structures for Continuous Generalisation: tGAP and SSC, pages 83–118. Springer International Publishing.	1.
4	Šuba, R., Meijers, M., Huang, L., and van Oosterom, P. (2014b). Continuous Road Network Generalisation. In *Proceedings of the 17th ICA Workshop on Generalisation and Multiple Representation, Vienna, Austria, September 23, 2014*, pages 1–12.	2.
4	Šuba, R., Meijers, M., and van Oosterom, P. (2015). Large scale road network generalization for vario-scale map. In *Proceedings of the 18th ICA Workshop on Generalisation and Multiple Representation, Rio de Janeiro, Brazil, 21 August, 2015*, pages 1–10.	3.
4	Šuba, R., Meijers, M., and Oosterom, P. v. (2016b). Continuous road network generalization throughout all scales. *ISPRS International Journal of Geo-Information*, 5(8):145.	4.
5	Meijers, M., Šuba, R., and van Oosterom, P. (2015). Parallel creation of vario-scale data structures for large datasets. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-4/W7:1–9.	5.
6	Šuba, R., Meijers, M., and van Oosterom, P. (2013). 2D vario-scale representations based on real 3D structure. In *Proceedings of the 16th ICA Generalization Workshop*, pages 1–11. The paper for ICA worshop 2013/Dresden.	6.
6	Šuba, R., Meijers, M., Huang, L., and van Oosterom, P. (2014a). An area merge operation for smooth zooming. In Huerta, J., Schade, S., and Granell, C., editors, *Connecting a Digital Europe Through Location and Place*, Springer Lecture Notes in Geoinformation and Cartography, pages 275–293. Springer International Publishing. ISBN: 978-3-319-03611-3.	7.
6	Huang, L., Meijers, M., Šuba, R., and van Oosterom, P. (2016). Engineering web maps with gradual content zoom based on streaming vector data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 114:274 – 293.	8.
6	Šuba, R., Driel, M., Meijers, M., van Oosterom, P., and Eisemann, E. (2016a). Usability test plan for truly vario-scale maps. In *Proceedings of the 19th ICA Workshop on Generalisation and Multiple Representation, Helsinki, Finland*.	9.