7 Conclusions

This thesis has researched further design and development of a system for vario-scale maps. Section 7.1 presents our ultimate vario-scale goal, which will give us perspective to understand issues addressed in the previous chapters such as further development of current generalization tools considering better vario-scale content (Chapter 4), processing of a large dataset not fitting in main memory (Chapter 5) and smooth user interaction (Chapter 6). All these aspects are now brought together in this chapter where they will be summarized and critically evaluated. The main contributions will be put in the context of the thesis by answering the research questions in Section 7.2, meanwhile new open questions and recommendation for future research will be covered in Section 7.3.

§ 7.1 Ultimate target for a vario-scale map system

Before we summarize the individual chapters, it is important to remind the reader of the ultimate target of vario-scale research. It started many years back and it developed via various improvements covered in different projects. However, the research has always been towards an optimal solution which can be characterized in the following characteristics:

I. The fully automated generalization process will provide good cartographic result comparable to NMA's products.
II. The map contains all map geometry types (points, lines, areas).
III. It will also include all type of map elements such as labels and POI.
IV. User will be able to navigate naturally throughout all scales.
V. Software will be able to process/handle an 'arbitrary' big dataset without any issues concerning cartographic quality.
VI. The generalization result will preserve topological correctness, and a full smooth 3D representation (smooth SSC cube).
VII. The solution will use well optimized progressive data transfer over the web.
VIII. Users will enjoy the smooth navigation even with limited bandwidth.
IX. The whole structure does not have to be recomputed when a small change of source data takes place.
X. It will support higher dimensions of data where, for instance, 3D data integrated with scale makes 4D Space-Scale-hyperCube.

The list above present our vision which drives the whole research line. This can be used as a context for evaluation or comparison. It also helps identify the main achievements of the PhD project.

§ 7.2 Answers to research questions

To realize technological shift in vario-scale described in previous section we raised few research sub-questions at the beginning of this thesis. Here, we provide the answers.

SUB I: *How much is the current map generalization process automated?*

Chapter 2 studied current development in the field of automated generalization. We have used output from two workshops three years apart to compare the solution for majority of European NMAs. It shown that NMAs use automated generalization in some way to provide good multi-scale representation, but it is still rapidly developing at this moment. Rarely, are there complete solutions of full automated production lines. Moreover, with current technological shift and more often budget cuts we can only assume that this tendency will continue in the future.

Other aspect is that NMAs were the main driving force so far, but this is changing. One can observe that users are starting to prefer free up-to-date data instead of cartographically correct data in longer update cycle as provided by NMAs. Moreover, in research publications significant shift to more a gradual representation is being seen, either by generating intermediate scales, morphing or continuous generalization.

This perspective shows that the research such as vario-scale is still crucial and could significantly contribute in the automated map generalization field.

SUB II: *What is the state of the art vario-scale map?*

Chapter 3 has shown the state-of-the-art prior to this PhD research. It has presented a geometrical non-redundant, variable-scale data structure in detail. The previous developments where summarized: from the GAP tree with some geometry redundancy to the topological GAP tree very well suited for a web environment where progressive refinement of vector data is supported. Additionally, it presents full 3D SSC representation (smooth tGAP), where all generalization actions lead to a smoothly changing map. A small change in the map scale results in a small geometry change.

It was shown in retrospect that the principles designed in the past are still valid and can be used for further development. Moreover, this forms the solid foundation for further development covered in this thesis.

SUB III: *How can we produce improved vario-scale data content?*

Chapter 4 focused on improving quality of content in vario-scale maps. It aimed at line features (road network) for the whole scale range, from the large, where roads are represented as areas, to mid- and small scales, where roads are represented progressively more frequently as lines. As a consequence of this process, there is an intermediate scale range where at the same time some roads are represented as areas, while others are represented as lines.

We designed a data model together with a modification of the data structure. This model is based on the integrated and explicit representation of: (1) a planar area partition; and (2) a linear road network. This enables the generalization process to include the knowledge and understanding of a linear network.

It has been presented on samples of real world data together with graphs, effectiveness analyses that automated generalization with gradual changes may lead to a reasonable results. In addition, we investigated the issue of better classification of objects during the generalization process and suggest further improvement with the groups.

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

Chapter 5 shown our generic strategy to handle really huge datasets. We proposed and tested an approach to obtain a vario-scale data structure of massive datasets. We have described all steps of the process chain which we applied and tested the approach with real data.

Our solution is based on the idea of subdividing the workload according to the Fieldtree organization: a multi-level structure of space. It subdivides space regularly into fields (grid cells), at every level with a shifted origin. Only features completely fitting within a field are processed. It has been shown that our approach is generic and works for different types of input data such as land cover or road network data. We have presented two approaches for scheduling the parallel work. One open problem is formed by very large features which are only treated in the higher-levels or even top-level of the Fieldtree, i. e. postponing the actual generalization for a (too) long time.

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

Chapter 6 presented the a benefits of smooth representation, leading to a better user experience. It has also presented aspects of zoom; *rescaling*, *content zoom* and *graphic techniques*, supporting the concept of a truly smooth vario-scale structure where a delta in scale leads to a delta in the map. Then three algorithms for the merge operation to generate smooth vario-scale structure were presented in Section 6.3 where the algorithm 'eater' was shown to be the best candidate for further development, because of its generality and the fact that it always leads to a solution. On top of that to use and validate the smooth vario-scale structure we developed our visualization prototype 'Intersector'.

SUB VI: *How do the users perform with vario-scale map compare to multi-scale map?* An

initial usability test in Section 6.5 tried answer this question. We used 'light' version of our visualization prototype 'Intersector' for vario-scale data and performed an initial test for small group of participants. The result of preliminary testing was inconclusive. Therefore our hypothesis that vario-scale could be faster and better for user interaction cannot be confirmed and requires more investigation. Nevertheless, it helps us identify major obstacles and understand some factors which play significant role in user experience. Among these factors are; size and quality of generated datasets, styling, GUI and the perception of zoom action. The gained knowledge was reflected in Section 6.7, where the smooth zoom operation is discussed. We believe that if we include all elements of the experiment in their finest developed stage the question can be answer in the next usability test.

More specific aspect of vario-scale concept were addressed by sub-questions above in separate chapters. After addressing these sub-questions we have to address the main research question.

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

Everything developed so far was designed in such a way that it fits in one prototype. It guarantees homogeneous solution targeting the ultimate goal presented at the beginning of this chapter, see Section 7.1. Our prototype is open source and it is shared in a repository. The code is available on following link:

`varioscale.bk.tudelft.nl`

Figure 7.1 visualises a system for vario-scale. It shows a pipeline, from a preprocessing step to the clients where data can be visualized. The architecture captures two main branches; 1) for progressive data transfer over the network which was covered in other research, 2) for smooth user experience based on SSC data. The system has been designed based on previous research. By putting individual links of the processing chain together we can see the relationships among the links and better understand our contribution (bold in Figure 7.1). We have:

- shown how the line features in our current vario-scale solution may be introduced;
- proposed a strategy provides the fully-automated generalization process that preserves a road network throughout all scales;
- investigated possibility for better classification of object with the groups during the generalization process;
- shown how to process really huge input dataset in the tGAP data structure;
- presented three algorithms for generating smooth conceptual 3D SSC model;
- develop SSC viewer (Intersector) to visualize and to experiment the data;
- performed an initial usability study;
- suggested improvements for future usability test;
- designed smooth zoom action to improve user experience.

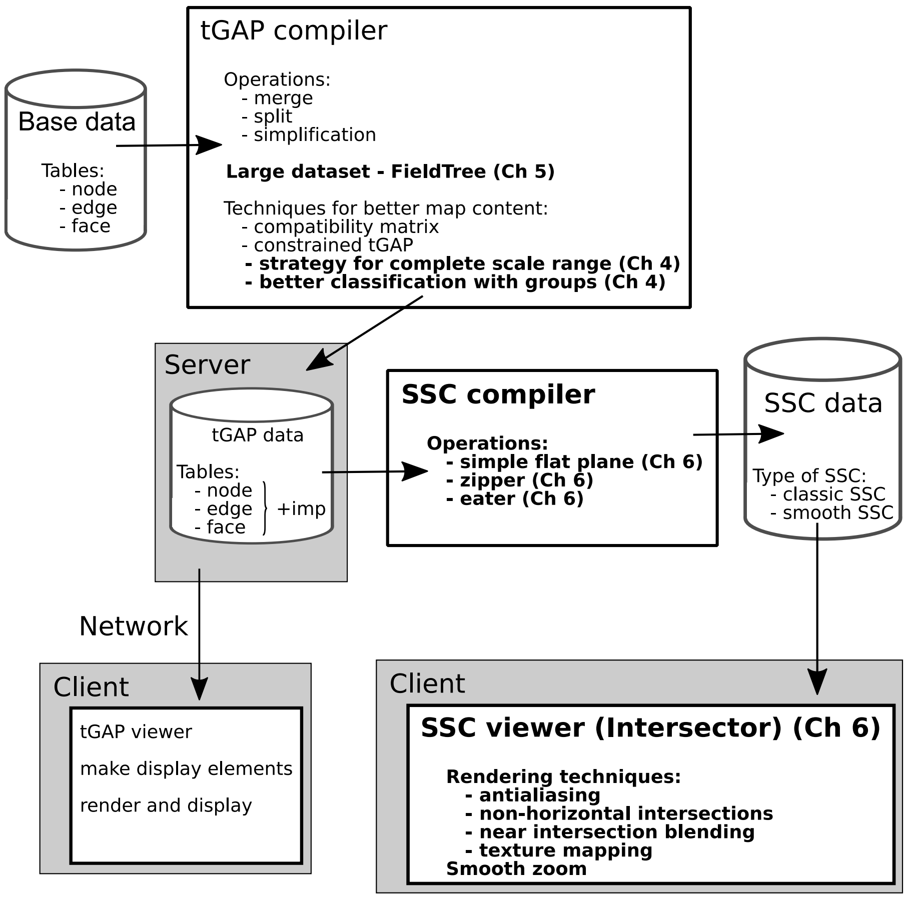

FIGURE 7.1 Diagram of a system for vario-scale maps. The contributions covered in this thesis are in **bold**.

§ 7.3 Recommendation for future work

For future research, several directions can be explored to continue with the research. Extensive list of open questions were provided in Chapter 3. Some of them were addressed in this thesis. Others are newly arising and originate from research covered in this thesis.

DATA UPDATE The current data structure is static one. It does not support any data editing. If some modification of data is made the whole structure must be recomputed. The same is true for the temporal aspect, there no version control system integrated in the structure *i. e.* going back in time is not an option. Being able to perform incremental update or any kind of data modification would be beneficial. Especial when the size of the data grows.

STYLES FOR VARIO-SCALE DATA Proper theme or colour design was not researched yet. Technical aspects and content of the structure had priority. However, aesthetic aspects of the results are important as well. Especially with more user testing in the near future. For instance, use of the same colour schema as input dataset for entire scale range does not seem correct. We should research styles for vario-scale data which do not distract users. For example, what should be the proper graphic visualization and styling of the road segment which change representation from area to line throughout the scales?

OTHER MAP FEATURES Some map features are still missing in the vario-scale concept such as Labels or POI. They are an important part of maps, but are not included in the structure. Objects in the map need a label and every label in the map takes space. It is a classical cartographic problem: each object that has to be labelled allows a number of positions where the corresponding label can be placed. However, each of these label candidates could intersect with label candidates of other objects. It is possible to find the right solution for just one predefined selected scale, but how can we find the right solution for the variable-scale?

ORCHESTRATION OF MORE TOOLS The list of operations is expanding. Our current prototype can run multiple processes at the same time. For instance, (1) algorithm dealing road network (preserving connectivity or roads), (2) processing large dataset by chunking the domain. Now, the question is how we can make possible that those two work together?

RELATION BETWEEN STEP AND SCALE The vario-scale content is produced as a sequence of steps–successively more generalized maps, so that these maps go well together instead of considering each level of generalization independently. In our perspective, the sequence of generalization steps is valuable. Our method has no explicit lower and/or upper bound with respect to the scale-range we target. This makes the method very generic. On the other hand, it is difficult to compare with current maps because it is different in principle.

DIFFICULT QUALITY ASSESSMENT Objective validation of the cartographic quality of the results is difficult. Direct comparison of the vario-scale map with existing multi-scale solutions is not adequate. Both approaches are different in principle and not really comparable. Therefore user testing together with quantitative metrics provide the only conclusive validation at this moment. New metrics for quality assessment should be researched.

IMPROVE DECISION MAKING In current selection in every process step the least important object is selected and some action is performed *e.g.* an object is collapsed or merge with its neighbour. This is done based on some condition. However, these conditions are very strict. It may not be optimal for map generalization in general, where local criteria should be in harmony with global conditions. Therefore, some more flexible or $fuzzy$ condition could provide a better solution.

WEB-SERVICES BASED ON 3D GEOMETRY Chapter 6 presents an idea that the user impression can be improved if the map is retrieved from 3D geometry (slice of the SSC prisms); First, 3D geometry is generated. Second, a slice of the geometry is calculated. Third, final maps based on the slice is constructed. In principle, it should be possible to use such a functionality in web-services setting. However, the optimal distribution of work in the web-client pipeline is not know, *e.g.* all can be performed on server side and only the final map is retrieved, or 3D geometry is sent and slicing and map construction take place on client side. There are more options possible but the optimal configuration is not known.

PROGRESSIVE DATA TRANSFER FOR 3D Furthermore, since the method is based on the data structure optimized for progressive transfer as has been shown for 2D vector data in (Huang et al., 2016), the same could be done for 3D data in theory. How can we keep data transfer at a minimum also for explicit 3D storage, and is explicit 3D storage really needed? Storing the data in a 3D topology data structure could be one option. Another option could be to derive what is needed from the tGAP data structures that store more or less separately the 2D geometry and 1D scale range and create the 3D representation when needed, *e.g.* at client side for slicing and map constructing.

HIGHER DIMENSIONALITY OF VARIO-SCALE DATA Higher dimensionality of vario-scale data is not explored. When we integrate 3D SSC with scale leading to integrated 4D Space-Scale-hyperCube data. Then the intersection of this 4D hypercube with the hyperplane gives a perfect 3D topology (no gaps or overlaps). This could solve a big problem as is often the case in the transition from one Level of Detail (LOD) to the next LOD in computer graphics.

MORE CONCLUSIVE USABILITY TESTING Initial user testing was done with small groups of participants and differences in the results were minor, and therefore can be considered as inconclusive. However, it was only a starting point in the research into user perception of vario-scale. We still believe that with proper map, environment, styling and GUI significant results can be achieved in near future. In long term, more testing should follow such as different generated SSC cubes, alternative visualization technique with various intersection shapes or different zooming techniques. All these have an effect on users and only basic options have been tested so far.