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ABSTRACT

This paper presents a methodology developed for a study to evaluate the state of the art of automated map generalization in commercial software without applying any customization. The objectives of this study are to learn more about generic and specific requirements for automated map generalization, to show possibilities and limitations of commercial generalization software, and to identify areas for further research. The methodology had to consider all types of heterogeneity to guarantee independent testing and evaluation of available generalization solutions. The paper presents the two main steps of the methodology. The first step is the analysis of map requirements for automated generalization, which consisted of sourcing representative test cases, defining map specifications in generalization constraints, harmonizing constraints across the test cases, and analyzing the types of constraints that were defined. The second step of the methodology is the evaluation of generalized outputs. In this step, three evaluation methods were integrated to balance between human and machine evaluation and to expose possible inconsistencies. In the discussion the applied methodology is evaluated and areas for further research are identified.

1. Introduction

Research in automated map generalization has yielded many promising results (Mackaness, Ruas, & Sarjakoski, 2007). At the same time, vendors face difficulties in implementing automated generalization solutions in commercial software (Stoter, 2005), which occurs for several reasons.

First, a formal definition of map specifications is lacking. Although a satisfying generalization solution can be defined in general terms—e.g., as a map that reduces the details and discerns regional patterns, that is aesthetically pleasant, and enables users to succeed in a given task (Mackaness & Ruas, 2007)—it is difficult to specify specifications into such a format and knowledge level in such a way that they can steer the automated generalization process. Second, software vendors need map specifications that are shared by several map producers such as National Mapping Agencies (NMAs) to justify their investments. Such shared generalization specifications are not easy to formulate because of differences in data models, level of detail of initial data, landscapes to be mapped, scales to be produced, etc. A final reason for the difficult implementation of automated map generalization is that generalization is a subjective process in which more than one ideal generalization result is often possible. This subjectivity in solving cartographic conflicts is a challenge to automate.

To address these difficulties, we conducted a study on the state of the art of automated map generalization in commercial software. Specifically, through the study we aimed to learn more about generic and specific map specifications of NMAs, to encourage and support vendors in implementing these specifications in commercial software, and to identify areas for further research. The study took place in the framework of EuroSDR (European Spatial Data Research), where NMAs, research institutes, and private industry work together on research topics of common interests.

The present paper focuses on the methodology that we developed to evaluate complete maps, generalized by different systems and different testers, taking into account the differing map specifications of several NMAs. The methodology had to consider all kinds of heterogeneity to guarantee independent testing and evaluation of available generalization solutions. To meet these heterogeneities,

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the methodology consisted of two main steps: requirements analysis for automated map generalization and evaluation of generalized outputs.

Our paper starts with an overview of previous research related to defining specifications for automated map generalization in Section 2. This section also defines the scope of the current study. Section 3 describes the first main step of the methodology, i.e., the requirement analysis. This step consisted of sourcing representative test cases, defining map specifications as generalization constraints, harmonizing constraints across the test cases, and analyzing the types of constraints defined. Section 4 presents the second main step of the methodology, i.e., the evaluation of generalization outputs. This step included developing and integrating three evaluation methods: expert evaluation, automated constraint-based evaluation, and qualitative comparison of outputs. The paper concludes with an evaluation of the methodology, sharing insights obtained during the tests, and identifying areas for further research (Section 5).

2. Background

2.1. Previous research related to specifications for automated map generalization

An overview of previous studies on formalizing map knowledge for automated generalization can be found in Sarjakoski (2007). Various researchers have studied specifications for automated map generalization (Foerster, Stoter, & Kraak, 2009). Müller and Mouwes (1990) examined existing map series to conclude that "superficial" generalization knowledge exists in the form of map specifications written down for interactive generalization. Complementary to this "superficial" knowledge, cartographers use "deep" generalization knowledge to interpret superficial knowledge. This deep knowledge is much harder to automate. Rieger and Coulson (1993) carried out a survey among a group of cartographers performing interactive generalization and concluded that a common view on the classification of generalization operators does not exist. Nickerson (1991) and Kilpelaïnen (2000) acquired knowledge from experts to define rules for knowledge-based map generalization. Various studies used reverse engineering to collect generalization knowledge by comparing map objects across scales (Buttenfield (1991), Leitner and Buttenfield (1995), and Weibel (1995)). Other studies generated rules from interactive generalization carried out by a cartographic expert (Weibel (1991), Weibel, Keller, and Reichenbacher (1995), McMaster (1995), and Reichenbacher (1995)). Several studies applied machine learning techniques to convert expert knowledge into map specifications for automated generalization, e.g., Weibel et al. (1995), Plazanet, Bigolin, and Ruas (1998), Mustiere (2001, 2005) and Hubert and Ruas (2003). Brewer and Buttenfield (2007) ran map exercises with students, on different datasets at various scales, to provide guidelines for generalization processes.

Our study builds primarily on the research by Ruas (2001), which took place within the European Organization for Experimental Photogrammetric Research (OEEPE; the predecessor of EuroSDR) and investigated the state of the art of generalization by evaluating different interactive generalization software. Ruas's study aimed to obtain insight into generalization processes for cartographic purposes—not to evaluate generalization packages or complete generalized output. The OEEPE study tested five platforms on three generalization cases for a selection of themes. Generalization operators on individual objects or groups of objects were triggered by testers' interaction. Because of a lack of written specifications, the target maps served as examples. Templates developed for the project included lists of cartographic conflicts, operations, and algorithms.

Several of Ruas's recommendations are relevant for the methodology presented in our paper. First, a formalized description of specifications for the output maps should help to obtain better solutions. Furthermore, tests should be evaluated by a more flexible and digital method, since the manual tracing of all testers' output in Ruas's study was extremely labor-intensive. Finally, tests should use symbolization information to standardize the outputs. In our study we have implemented all of these recommendations.

2.2. Scope of the current study

The two main questions of our study were:

(1) What are the possibilities and limitations of commercial software systems for automated generalization with respect to NMA specifications?
(2) What different generalization solutions can be generated for one test case and why do they differ?

Several aspects defined the scope of the study.

First, the aim of the study was to obtain knowledge on different aspects of automated map generalization with respect to NMA specifications, and to discover how these are implemented in commercial software. The potential and limitations of individual systems were therefore not relevant.

Second, our study focused on map specifications of NMAs. The study did not consider specifications of map end-users, because surveys performed by NMAs among their customers showed a continuous need for traditional, paper maps representing topography at different scales. This implies that NMAs still have to produce traditional map series, and justifies our focus on NMA map specifications. Although this study is driven by large volume (paper) map production at NMAs, one should realize that the results are highly relevant for other map producers and for web mapping.

Third, our study focused on large- to mid-scale generalization, since the involved NMAs considered this the most time-consuming generalization task of current production lines.

Fourth, our study focused on complete maps, rather than on specific situations. Therefore, the generalization processes should not be a sequence of operations triggered by conflicts on individual objects or a group of objects as in Ruas's OEEPE research, but be triggered by object class (theme) or spatially indicated areas (partitions).

A final focus of the study was to limit the tests to commercially available versions of software to allow us to conclude on generalities. Consequently, research team testers, either experienced or inexperienced with the systems, were not allowed to customize the software nor to program new algorithms. This did not mean that the implementation of specifications was straightforward: all tested systems—ArcGIS (ESRI), Axpand/Genesys (Axes systems), Change, Push, Typify (University of Hannover) and Clarity (1Spatial) —provide considerable flexibility to deal with the specifications. Consequently, many decisions on how to express the specifications were left to the testers. In some systems testers had to decide on the order of addressing the specifications; in other systems they had to decide which algorithms and parameters values to use. Therefore, all tests required considerable effort to align the functionality of the systems with specific test cases. To enable vendors to show all the potentials of their system, they performed parallel tests in which they were allowed to customize and develop new algorithms.

3. Requirement analysis

This section presents the results of the requirements analysis. Section 3.1 describes the selection of test cases representing map generalization problems. Section 3.2 describes the formalization of NMA specifications for automated map generalization. Section 3.3 reports on the harmonization that was carried out to produce one generic set of formal map specifications within the context of our study. Section 3.4 analyzes the defined specifications to learn more about similarities and differences between map specifications of NMAs.

3.1. Selecting the test cases

The first step in the requirement analysis was the selection of test cases representing problems for automated map generalization. To meet this objective, we generated a list of outstanding map generalization problems based on the OEEPE research completed with the research team's own experience. Examples of these problems are building generalization in urban zones, mountain road generalization, solving overlapping conflicts in locally dense networks, pruning of artificial networks, and ensuring consistency between themes in particular areas such as coastal zones. Some of these problems have been tackled in research, resulting in at least partial solutions. However, we wanted to evaluate complete solutions in commercial systems, and, therefore, these problems were also identified as representative map generalization problems. We selected four test cases that included all these problems (see Table 1) provided by Ordnance Survey Great Britain (OSGB), Institute Geographique Nationale, France (IGNF), The Netherlands' Kadaster (Kadaster) and Institut Cartogràfic de Catalunya (ICC).

The NMAs of the test cases modified their datasets to prepare them as input for the generalization tests, e.g., details such as rich classifications were removed from the datasets and the datasets were translated into English. In addition, to be able to define specifications of the output maps with respect to symbolized objects and to assure uniform outputs, the NMAs defined symbols for the outputs. Fig. 1 shows cutouts of the source datasets.

3.2. Formalizing NMA specifications for automated map generalization

In the task of formalizing map specifications for automated generalization, we can distinguish between two stages. The first stage is to describe the specifications in a way that a user (in our case the testers of the systems) fully understand what (s)he should try to obtain with the system. The second stage is to translate these specifications in a format understandable by the generalization system. The first stage was completed by means of cycles between the data providers and the research team. The second stage was completed by the testers during the test process.

To implement research theories, we formalized map specifications of NMAs as a set of cartographic constraints to be respected. In previous research on generalization, the use of constraints is a common method to define specifications and to control and evaluate the automated generalization process. Examples are McMaster and Shea (1988), Beard (1991), Bard (2004), Barrault et al. (2001), Ware, Jones, and Thomas (2003), Burghardt and Neun (2006), and Sester (2000). Constraints express how generalization output should look without addressing the way this result should be achieved, e.g., by defining sequences of operations.

We developed a template for a uniform way to define constraints in the four test cases. In the template specific properties of the constraint can be defined such as condition to be respected and the geometry type and feature class(es) to which the constraint applies (see Appendices A–C and Table 3). The template distinguishes between constraints on one object, on two objects, and on groups of objects. An importance value indicates the importance of satisfying the specific constraint in the final output. This value does not indicate in what sequence the constraints should be solved (Ruas, 1999). Satisfying less important constraints first may be necessary to satisfy more important constraints later. For example, generalization of buildings should start with reducing density before trying to cope with overlaps, even though non-overlapping constraints are more important than density constraints. NMAs could also propose an action to support the tester in finding the most desired generalization solution. This is because in some cases NMAs know what action should be taken to meet the constraint optimally, e.g., the action "exaggerate detail" for constraint "minimal depth of protrusion of a building."

3.3. Harmonizing constraints

NMAs defined their map specifications for automated generalization in the developed template by analyzing text-based map specifications, software code, and cartographers' knowledge. Initially a large number of constraints were defined for the four test cases (about 250), which often covered similar situations.

In the next step we harmonized the constraints, which was needed for two reasons. Harmonization, resulting in the same constraints for similar situations, unified the tests. Once a tester had expressed the constraint for one test case, (s)he could perform the same actions to express a similar constraint for a second test case. Second, harmonization enabled us to compare results for similar constraints across the test cases.

For the harmonization, similar constraints across the four test cases were identified by carefully comparing the four constraint sets. The harmonization resulted in a list of generic constraints. A few constraints were so specific that they remained as a specific constraint. Examples are OSGB constraints addressing how buildings should be aggregated depending on the initial pattern. The harmonization process resulted in 45 generic constraints: 21 generic constraints on one object (see Appendix A), 11 constraints on two objects (see Appendix B), and 13 constraints on a group of objects (see Appendix C). The harmonized constraints describe those properties of the constraints that are generically applicable. These constraints contain blank entries to be completed by NMAs to define their constraints as specification of the generic constraints. The columns in the harmonized set (e.g., class, action, importance) only contain values when the value is applicable for any case, except for the column 'Condition to be respected' which is always filled, mostly with non-specified parameter values. In all other cases NMAs can specify their classes, actions, parameter values and importance values to define their constraints as specification of the generic constraints.

Table 2 shows examples of generic constraints on one object, two objects, and a group of objects (the constraint type will be introduced in Section 3.4).

Table 1
Test cases selected for the EuroSDR research.

Area type	Source dataset	Target dataset (k)	Provided by	No. of feature classes	Main feature classes
Urban area	1:1250	1:25	OS Great Britain	37	Buildings, roads, river, relief
Mountainous area	1:10 k	1:50	IGN France	23	Village, river, land use
Rural area	1:10 k	1:50	Kadaster, NL	29	Small town, land use, planar partition
Coastal area	1:25 k	1:50	ICC Catalonia	74	Village, land use (not mosaic), hydrography

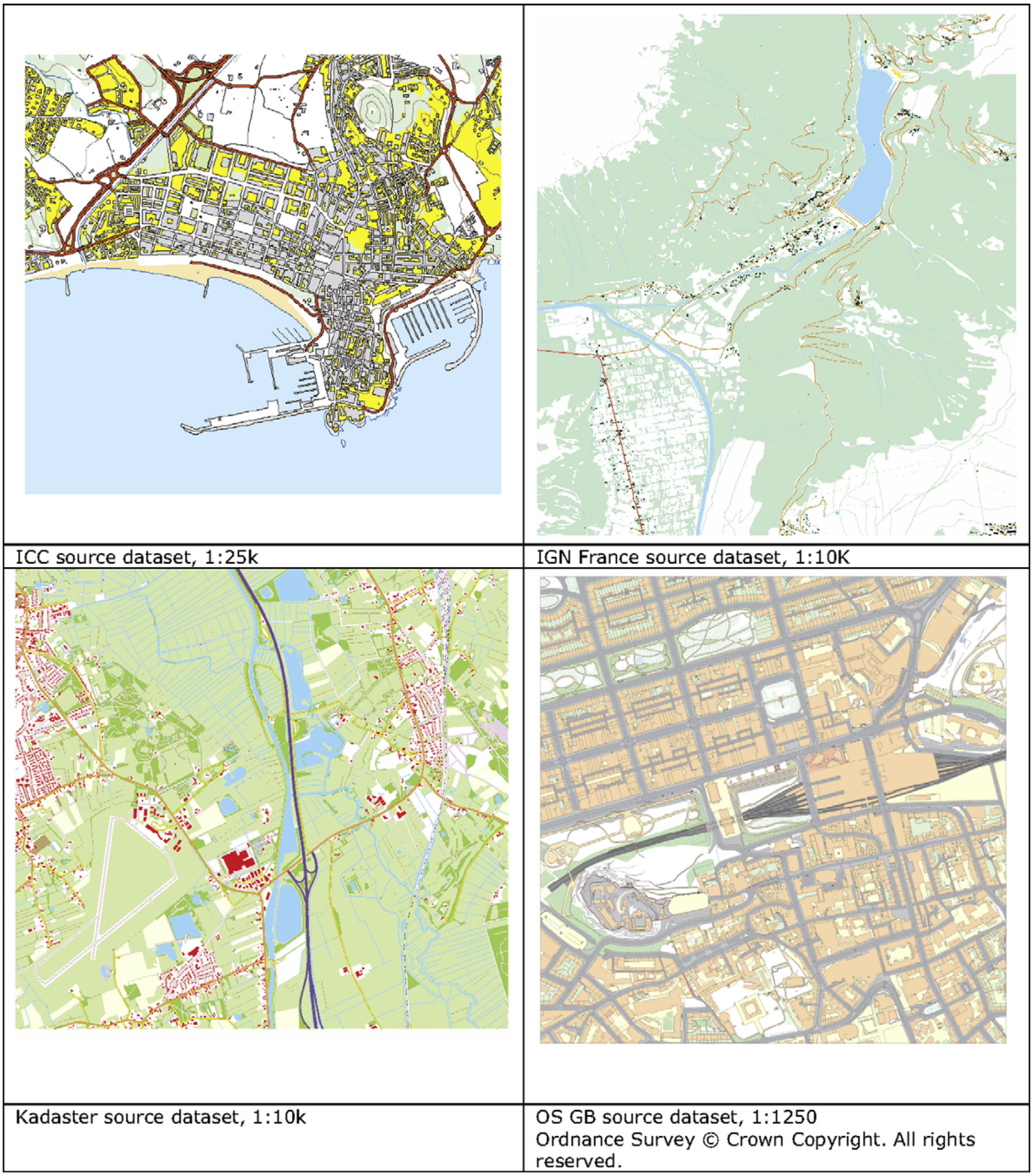

Fig. 1. Cutouts of source datasets in the EuroSDR generalization study. Maps are reduced in size.

After all four NMAs agreed on the harmonized constraints, they redefined their initial constraints as generic constraints using their own feature classes, thresholds, parameter values, and preferred actions, see Table 3 for an example of ICC (all NMA specific information is indicated in red).

3.4. Analyzing the test cases

To obtain more in-depth knowledge on NMA specifications for automated map generalization, the final step of the requirement analysis was the comparison of constraints across the four test cases.

For this comparison, one should realize that the constraint sets do not reflect all generalization problems of NMAs. First, the NMAs had to limit their constraints to those describing the main problems in the test area and to constraints that were more or less straightforward to formalize. Second, the constraints were defined without running any automated generalization process that would have shown both missing and unclear constraints. Last, the amount of time allocated to the testers would never enable them to set up the equivalent of a complete generalization production line, handling all specifications for one given map scale; therefore, NMAs limited their efforts on constraints that could be tackled within the context of the tests.

For the comparison of constraints among the four test cases we used three criteria: (1) the number of objects taken into account in the constraints, (2) the type of the constraints, and (3) the feature class for which the constraints were defined.

For the constraint type we distinguished between two main categories: legibility constraints and preservation constraints (Burghardt, Schmidt, and Stoter (2007)). Preservation constraints are completely satisfied at scale transitions. These are constraints

Table 2
Examples of harmonized constraints.

Constraint type	Property	Condition to be respected
Constraints on one object		
Minimal dimension	Area	Target area > x map mm^2; target area = initial area ±x%
	Width of any part	Target width > x map mm
	Area of protrusion/recess	Target area > x map mm^2
	Length of an edge/line	Target length > x map mm
Shape	General shape	Target shape should be similar to initial shape
	Squareness	[Initial value of angle = 90° (tolerance = ±x°)] target angles = 90°
	Elongation	Target elongation = initial elongation ±x%
Topology	Self-intersection	(Initially, no self-intersection) no self-intersection must be created
	Coalescence	Coalescence must be avoided
Position/orientation	General orientation	Target orientation = initial orientation ±x%
	Positional accuracy	Target absolute position = initial absolute position ±x map mm
Constraints on two objects		
Minimal dimensions	Minimal distance	Target distance >x map mm
Topology	Connectivity	[Initially connected] target connectivity = initial connectivity
Position	Relative position	Target relative position = initial relative position
Constraints on a group of objects		
Shape	Alignment	Initial alignment should be kept
Distribution & statistics	Distribution of characteristics	Target distribution should be similar to initial distribution
	Density of buildings (black/white)	Target density should be equal to initial density ±x%

Table 3
Example of ICC map specifications defined as constraints that extend the EuroSDR harmonized constraints.

Item in constraint template	Example on one object	Example on two objects	Example on group of objects
Constraint ID	ICC-1-22	ICC-2-21	ICC-3-18
Geometry type	Polygon	Polygon–line	Polygons
Feature class 1	Quay_adjacent_to_sea	Building	Building
Condition for object being concerned with this constraint	Depth of protrusion >1 map mm	Distance between building and road <0.5 map mm	
Constrained property	Width of protrusion/ recess	Orientation	Density of buildings (black/white ratio)
Condition depends on initial value?	No	Yes	Yes
Condition to be respected	Target width >0.2 map mm	Building must be parallel to road	Target density should be equal to initial density ±20%
Action	Collapse to a line		
Importance of constraint (1–5, 1 is less important)	3	3	3
Exception			
Schema to illustrate if needed			
Additional for constraints on two objects:			
Feature class 2		Road	
Condition for both objects being concerned with this constraint		Objects are parallel (±15°)	
Additional for constraints on group of objects:			
Kind of group			Urban block
Kind of objects of the initial data composing the group			Buildings surrounded by minimal cycle of roads (in urban areas)

prescribing topology, position, orientation, shape, and distribution/statistics. Preservation constraints may be violated when operations are applied for ensuring legibility (minimal dimensions and granularity). Legibility can be investigated independently of the source dataset, while preservation always has to be evaluated in correlation with the source data. Besides legibility and preservation constraints, we identified "model generalization" constraints. These refer mainly to constraints for removing certain feature types from the data (e.g., "cycle path" in the Kadaster test case or "wall" in the ICC test case). These constraints are also for avoiding aggregation of objects with different attributes; e.g., different types of buildings in the OSGB test case should not be aggregated.

Table 4 shows the results of comparing the four constraint sets using the three criteria. Several conclusions can be drawn from this table. First, the ICC test case contains a large number of constraints compared to the other cases. This can be explained by the large number of feature classes (see Table 1) resulting in several similar constraints for different types of roads. Second, most constraints are defined for one object in all four cases, whereas the fewest constraints are defined for groups of objects, most likely because it was difficult to define constraints on groups of objects. Third, constraints for ensuring minimal dimensions are important in all four test cases, showing the importance of these constraints in the cartographic generalization process. Another observation is that topological constraints are defined on a more general level such as "preserve topological consistency and connectivity," "self-intersection not allowed," or "keep adjacency." It is notable that there are only a few shape constraints defined by Kadaster. Position and orientation constraints are sparsely specified by all NMAs, and they refer only to buildings. One explanation could be that buildings are expected to be displaced more often than other objects during the generalization process. A final conclusion of this analysis concerns the feature classes that were included in the constraint definitions. All four test cases contain many constraints on buildings,

Table 4
Analysis of constraints of the test cases, classified on various criteria.

Test case	Total number of constraints	Number of objects			Constraint type								Feature classes involved							
					Model	Legibility	Preservation													
		On one object	On two objects	On group of objects	Model generalization	Min. dimension and granularity	Position	Orientation	Shape	Topology	Distribution/ statistics	Other	Building	Land use	Road	Water	Relief	Coastal features	Any	Other
ICC	137	86	23	28	12	80	0	4	19	12	5	5	39	20	16	25	8	19	9	1
Kadaster	52	27	21	4	11	18	1	0	1	6	0	15	10	13	23	3	0	0	0	3
IGNF	61	32	15	14	2	15	2	4	15	12	2	9	33	2	12	9	2	0	2	1
OSGB	49	24	13	12	2	16	1	0	0	8	0	22	24	1	8	1	8	0	2	5
Total	299	169	72	58	16	129	4	8	35	38	7	51	106	36	59	38	18	19	13	10

land use, and roads. The reason for the importance of these classes in the constraint sets is most likely because these are the most frequently occurring objects and the most significant for users of the map and therefore most (interactive) generalization is applied to these objects. The variation of constraints among other feature classes is a result of the relative importance of certain feature classes within the four chosen test cases; e.g., constraints on coastal features are dominant in the ICC case.

Every system was tested two to three times on all four test cases by generalization experts, who were both skilled and unskilled with the systems. In every test, the tester tried to translate all defined specifications into a form understandable by the specific software. After the testing, the outputs were evaluated using a methodology that is explained in the next section.

4. Evaluating generalized outputs

Evaluating generalized data can serve three main tasks: *evaluation for tuning* the generalization system prior to generalization, *evaluation for controlling* the generalization process during generalization, and *evaluation for assessing* the quality of generalized data after generalization (Mackaness & Ruas, 2007). The purpose of evaluating generalized data in our study falls in the last category. However, the evaluation serves a second, more specific aim, which is learning more about generalization processes.

The methodology that we developed to evaluate the generalized outputs of the tests was driven by an observation by Mackaness and Ruas (2007). They stated that an adequate evaluation framework should be able to handle the notion that the final output is a compromise among a set of sometimes competing map objectives. Such a framework should balance between human evaluation and machine evaluation to meet the complexity of evaluation; e.g., machine evaluation can direct the user to those parts of the solution that are deemed to be unsatisfactory.

Based on this observation and motivated by the constraint-based approach of the requirement analysis of our study, we developed three integrated methods for evaluating the generalized data:

1. qualitative evaluation by cartographic experts,
2. automated constraint-based evaluation, and
3. evaluation, which visually compared different outputs for one test case

The integration was accomplished by directing experts on situations that were well, badly, or differently solved according to the automated constraint-based evaluation. In addition, the results of the visual comparison of outputs were discussed with the experts of the test cases. Conclusions of one method are also compared with results of the other two methods to identify inconsistent measuring tools.

All 34 outputs produced by the tests were evaluated. These were 27 outputs delivered by research team testers and seven outputs delivered by vendors.

The three evaluation methods are explained in Sections 4.1–4.3. More details can be found in Burghardt et al. (2008).

4.1. Expert evaluation

For the expert evaluation, a survey was developed that extends the earlier experts' survey of the AGENT prototype (AGENT, 2000). The survey, completed by cartographic experts of the four NMAs, focused both on global indicators and on individual constraints. The global indicators used to assess the outputs are shown in Table 5. For the assessment of the outputs on individual constraints, it appeared to be impossible to visually assess whether a threshold

Table 5
Global indicators used in the expert survey.

Global indicators
Level of manual editions required to meet the constraints
Deviation from initial (undergeneralized) data
Preservation of the geographic characteristics of the test area (urban, mountainous, rural, or coastal area)
Legibility
Seriousness and frequency of major detected errors
Number of positive aspects
Information reduction (ungeneralization/overgeneralization)

value, as often used in the definition of the constraints, was met. Therefore, we summarized the original constraints in a set of constraints that could be visually assessed (see Table 6). Cartographic experts assessed how these derived constraints were solved: either very badly, badly, well, or very well.

At the end of the survey, experts annotated the output maps with examples of good (g), bad (b), and differently solved generalization solutions (d) (see Fig. 2).

4.2. Automated constraint-based evaluation

The automated constraint-based evaluation compared the measured final value (e.g., ''size') for a constraint with an ideal final value. For this evaluation an OpenJump prototype (OpenJump, 2008) was developed (see Fig. 3). This prototype implemented the automated evaluation of two legibility constraints: ''target area > x map mm^{2}'' (for one object) and ''target distance > x map mm'' (between two objects). The outcome of these evaluations is either 0 (perfect solution) or 1 (violated constraint).

Although the implementation of automated evaluation of these two constraints was more or less straightforward, the implementation for most other constraints appeared to be difficult and was therefore not realized. The reason for this is that the definition of constraints mainly aimed at being unambiguously clear for testers. Therefore, we did not endeavor to make them as formal as possible. Although for some constraints (e.g., shape and spatial distribution) it is known that the definition and the measurement are complex, a higher level of formalization could have been achieved. A constraint such as ''initial and generalized shape should be similar'' is less formal than the constraint ''preserving width–length ratio.'' For this reason specifically, the constraints defined for group of objects appeared to be very difficult (if not impossible) to evaluate in an automated manner; examples are constraints on networks, patterns, and spatial distributions.

To show to what extent automated constraint-based evaluation is appropriate to identify the quality of generalized data, we applied the prototype to interactively generalized data of Kadaster, scale 1:50 k (the target dataset of the test case of Kadaster). In this test we assumed that the interactively generalized data, which is currently in production, is a good generalization result.

We evaluated two constraints: minimum area of buildings and minimum distance between buildings. The results for the first constraint show that 27% of the buildings are smaller than the threshold (0.16 map mm^2) and are therefore evaluated as bad (see Fig. 4). However, when examining the data in more detail, we found that many ''too small buildings'' are just a little below the threshold size. The difference in minimum size, as mentioned in the written specifications (main source for the constraints) and as used in interactive generalization, can be explained in two ways. First, it is not possible for humans to distinguish between the threshold and the threshold plus/minus a flexibility range, and, therefore, cartographers use the thresholds with a notion of

Table 6
Individual constraints used in the expert survey.

Constraints on one object	Constraints on two objects	Constraints on a group of objects
Minimal dimensions	Spatial separation between features (distance)	Quantity of information (e.g., black/white ration)
Granularity (amount of detail)	Relative position (e.g., building should remain at the same side of a road)	Spatial distribution
Shape preservation	Consistencies between themes (e.g., contour line and river)	

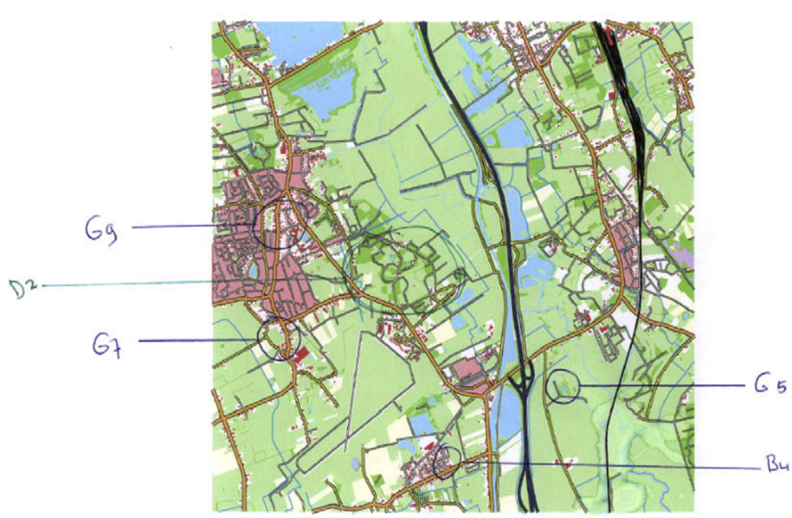

Fig. 2. Generalization output of the Kadaster test case, annotated by a cartographic expert.

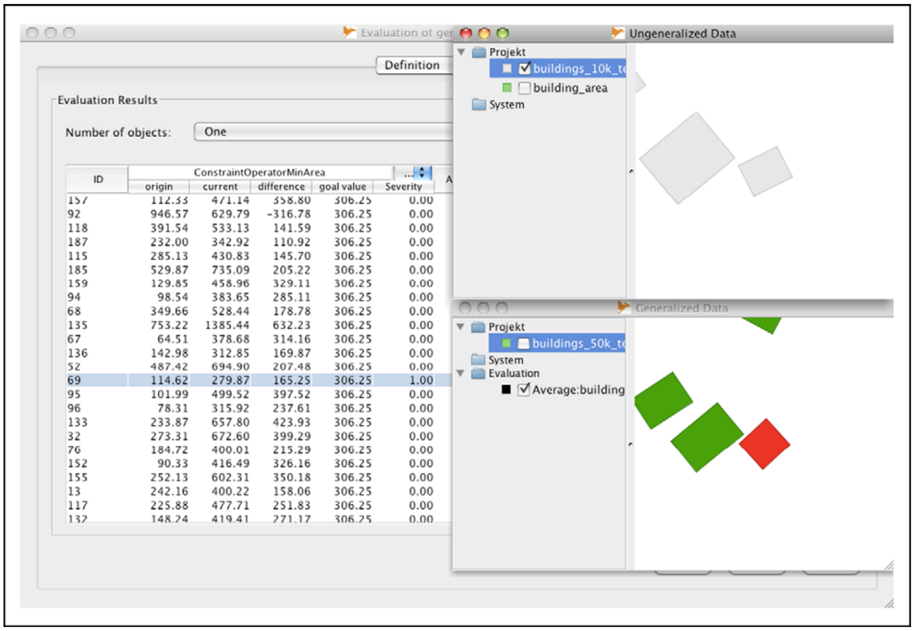

Fig. 3. Screen shot of prototype for automated constraint-based evaluation.

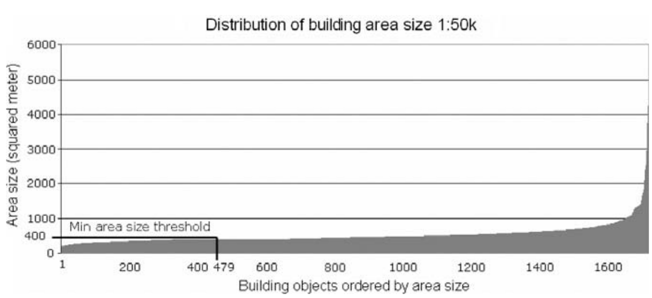

Fig. 4. Results of analyzing minimal building areas in interactively generalized data, scale 1:50 k.

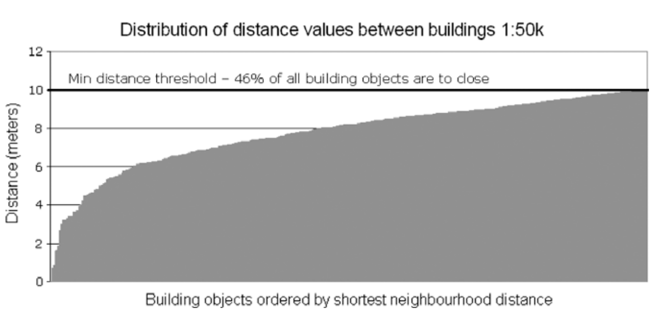

Fig. 5. Results of analyzing minimum distance between buildings constraint on interactively generalized data, scale 1:50 k. The non-violating buildings are not shown in this graph.

flexibility (Bard, 2004; Ruas, 1999). Second, in specific situations the cartographer may have chosen to relax the size constraint to meet a more important constraint, e.g., "keep important buildings."

The automated evaluation of the constraint on minimal distance (2 map mm) in the interactively generalized dataset also shows many violations of the constraint. 46% of the buildings are too close to each other (Fig. 5). The violations can partly be explained by the notion of flexibility and by deliberately violating constraints to meet more important constraints, as discussed above.

However, because of the high number of violations, we examined the violated situations in more detail and encountered many situations assessed as "bad," as shown in Fig. 6b and c. To be able to distinguish between Fig. 6a, on the one hand (in which the minimum distance constraint does identify a cartographic conflict), and Fig. 6b and c (which may be acceptable solutions), minimal distance between buildings should be further refined in constraint definitions.

The conclusion of this automated evaluation of interactively generalized data is that constraint-based evaluation requires further research to be able to describe the quality of generalized data. Future research should aim at better definition of constraints with respect to automated evaluation and better understanding of the impacts and dependencies of several constraints.

Section 5 (discussion and conclusion) contains several recommendations on how constraint-based evaluation can be improved to become more appropriate for assessing generalized data.

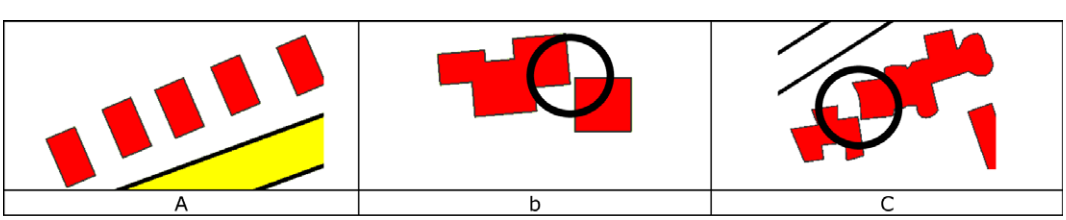

Fig. 6. Minimal distance constraint identifies unacceptable situations (a). Acceptable generalization solutions violate the distance constraint (b and c).

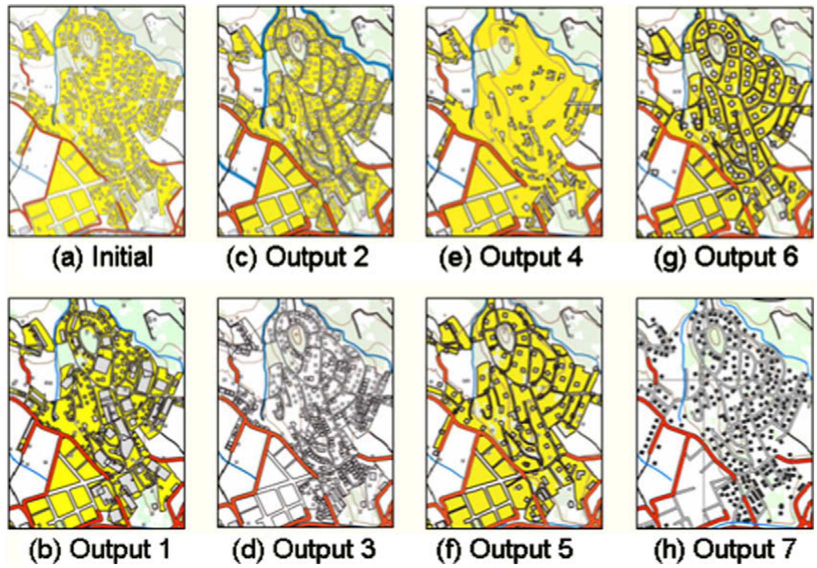

Fig. 7. Focus zone on generalization of buildings in suburban areas use to compare outputs for one test case. ICC initial data (a) and seven generalization outputs ((b)–(h)).

4.3. Visual comparison of outputs

The objective of the visual comparison of generalized data was to describe the differences between outputs for one test case from a qualitative point of view and to explain the differences. The evaluation carefully examined three to five zones per test case, which were identified by the NMAs as being of particular interest. Examples are buildings and streets in cities and suburban areas, coastlines, road interchanges, parallel roads, mountainous roads, vegetation, and dense channel networks. Fig. 7 shows an example of such a focal zone (buildings in suburban area) in the outputs of one test case. This evaluation obtained insights into the interdependencies between different constraints, the completeness and clarity of constraints, and the influence of testers' experiences with both the systems and data on the generalized output.

5. Discussion and conclusions

In this paper we have presented the evaluation methodology we developed to assess generalization outputs produced by various software packages and different testers, taking into account the differing specifications of the participating NMAs. From the development and application of the methodology, several conclusions can be drawn that identify issues for further research.

5.1. Defining map specifications as constraints

The definition and harmonization of constraints formalizing NMA map specifications provided a common view on requirements for automated map generalization. Although very time consuming, defining map specifications as a set of constraints was a good experience for the NMAs, because it highlighted the importance of explicitly defining NMA data and mapping specifications for automated processes.

The harmonized list of constraints as a result of our study is, however, not complete. The NMAs had to limit their constraints to those describing the main problems within the selected test areas and to constraints that were more or less straightforward to formalize. In addition, the constraints were defined without running any automated generalization process, which would have shown both missing and unclear constraints as well as how specific constraints work in practice. Nonetheless, the resulting set of constraints is a first attempt to define a "full" set of constraints as implementation of research theories.

5.2. Formalizing and evaluating preservation specifications

The preservation specifications were more difficult to formalize and to evaluate than the legibility specifications. Therefore, better understanding of preservation specifications is required to improve their formalization in constraints as well as the measurement of constraint violation. This includes a better understanding of the concepts involved (i.e., how to mathematically describe "shape") and of the changes allowed (how to mathematically describe accepted modifications). Harrie (2001) obtained such information by studying existing maps at different scales.

Another problem in evaluating preservation constraints is that a correspondence is required with the initial data. This is not an issue in 1:1 relationships; however, because of operators as selection, typification, amalgamation, and aggregation relationships may become complex, which makes it difficult to compare output data with the initial data.

The difficulty of evaluating preservation specifications was also encountered in the expert survey: it was often unclear whether a preservation constraint was assessed as "good" because the system had carefully accounted for it, or because the system had simply ignored it and at the same time had not much altered the data during the process.

5.3. Generalizing through constraints

Our methodology used constraints mainly to determine to what extent the outputs met the specifications. Our evaluation, which integrates three methods, has shown that this approach has an important limitation: the results for individual constraints are not always a good indicator for the quality of the overall solution. This has various explanations. First, some constraints may have been violated deliberately to enable good results for other constraints, e.g., by allowing (slightly) more displacement to avoid overlap. Second, as was observed in the automated constraint-based evaluation of interactively generalized data, one should assess not only *if* a constraint was violated but also if the violation yields an unacceptable cartographic conflict. Third, very good results for one specific constraint (e.g., minimal distance between buildings) may coincide with bad results for another constraint (e.g., building density should be kept). Fourth, a non-satisfied constraint can be due to missing functionality in a system, but can just as well be due to imprecise constraint definition. And finally, as Harrie and Weibel (2007) observed, results of constraint-based evaluation heavily depend on the defined test cases: is the constraint set complete and evenly balanced, or does it contain many constraints for very specific situations (as in the OSGB case)? Therefore, future research should aim to:

(a) revise the threshold values of constraints copied from map specifications, because their use differs in interactive and automated processes. This would require introducing the notion of flexibility in the formalization and evaluation of constraints for automated processes.
(b) evaluate the legibility constraints that account for this flexibility as a satisfaction range between 0 and 1, instead of a Boolean outcome. Boolean values may more appropriate to identify cartographic errors. They may, however, be less appropriate for assessing the evaluation output, because they do not provide information on the degree to which the threshold is ignored.
(c) improve operators (algorithms) in generalization systems by applying the notion of satisfaction ranges.
(d) validate the constraint approach by considering how to aggregate "constraint-by-constraint" assessments for global indicators of map quality, specifically by better understanding their interdependencies and impact. This also raises questions on the domain of constraint satisfaction and violation values and on their weighting and prioritizing to make different constraints comparable and to enable aggregating them to global indicators. These issues have previously been addressed in the domain of constraint-based optimization (see Bard, 2004; Ruas, 1998, and Mackaness & Ruas, 2007).

5.4. Improving the constraints

In addition to our recommendation to incorporate the notion of parameter value flexibility in improved versions of the constraints, our results suggest three specific recommendations for improving the constraint-based definition of map specifications. First, the constraints should be as formal as possible to support the generalization process as well as the automated-constraint-based evaluation. This implies that general concepts, such as shape, pattern, and urban and settlement structures, should be described formally. Second, constraints that were missing as observed from the outputs should be added. Finally, constraints that appeared to be unclear need refinement to distinguish, e.g., cartographic conflicts from acceptable solutions (compare Fig. 6a with Fig. 6b and c). Currently constraints are usually defined for geometric or thematic properties. Improvements could come from cognitive science.

5.5. Evaluating generalization software beyond constraints

Our study concentrated on the question of whether commercially available solutions could meet the map specifications of NMAs defined as constraints. However, during our tests several other aspects were encountered that are also relevant for assessing commercial generalization systems. For example, our testers found that in some cases topological errors were introduced during the generalization process, and that links between generalized and ungeneralized objects, required for automated evaluation, were lost in most of the outputs. Also conflict detection tools are missing. These aspects should be addressed in future tests.

Furthermore the tests highlighted difficulty to parameterize the complex algorithms and the lack of default tools, for instance default algorithm sequences or default constraints. Appropriate tools to optimally parameterize existing algorithms for a specific test case would highly improve the applicability of commercial software for a specific test case. Therefore a next research could address parameterization possibilities.

In addition, a future test should address aspects not amenable to constraints. The constraint approach is based on the consequences of scale changes. According to Mackaness and Ruas (2007), this bottom-up approach might work better for small-scale changes. In contrast, a top-down approach that meets the consequences of (large-) scale reduction by choosing appropriate representations for phenomena might work better over larger scale changes where changes are much more fundamental. A future test can provide more insights into the appropriateness of both approaches for automated map generalization. Indeed, it appeared that constraints on the final result are sometimes not sufficient to fully express without ambiguity what is expected. In some cases, specifying the expected transformation can help if this transformation is always the same and if it is well known. However fuzzy and incomplete constraints resulted in very different interpretations and solutions among the testers, which may ask for a different approach in defining the requirements for automated generalization. Furthermore, because the limited sizes of the four test cases precluded addressing the problems of dealing with large amounts of data (computational complexity, potential memory overflows that necessitate data partitioning, presence of numerous and various particular cases that make some algorithms fail, etc.), future tests should define criteria as well as measuring tools to assess scalability of systems.

And finally, future tests should quantify customization possibilities. The most realistic way to address NMA specific requirements may be to customize existing software. This requires facilities for writing extensions or for allowing integration with other systems.

In conclusion, our comprehensive study and new methodology are a significant contribution to generalization research, specifically to better defining map specifications and evaluating generalized maps. Future generalization research can extend our methodology and make use of our findings, applying improved versions of the constraint sets and re-using our carefully sourced generalization test cases.

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Appendix A. Appendix Harmonized constraints for one object

GENERIC-constraint ID	Constraint type	Geometry type	Class	Condition for object being concerned with this constraint	Constrained property	Condition depends on initial value?	Condition to be respected	Action	Importance of constraint (1–5, 1 is less important)
EuroSDR-1-1	Minimal dimensions	Polygon			Area	No	Target area >x map mm^2	IF final area <x map mm^2 THEN {action}	
EuroSDR-1-2	Minimal dimensions	Polygon			Width of any part	No	Target width >x map mm		
EuroSDR-1-3	Minimal dimensions	Polygon		Initial area > <= x map mm^2	Area	Yes	Target area = initial area ± x%		
EuroSDR-1-4	Minimal dimensions	Polygon		Polygon contains a hole	Area of any hole in a polygon	No	Target area of hole >x mm^2		
EuroSDR-1-5	Minimal dimensions	Line/polygon			Length of an edge/line	No	Target length >x map mm		
EuroSDR-1-6	Minimal dimensions	Line/(polyline)			Width	No	Target width >x map mm		
EuroSDR-1-7	Minimal dimensions	Line			Vertices density	No	Target vertices distance >x map mm		
EuroSDR-1-8	Minimal dimensions	Polygon			Width of protrusion/recess	No	Target width >x map mm		
EuroSDR-1-9	Minimal dimensions	Polygon			Depth of protrusion/recess	No	Target depth >x map mm		
EuroSDR-1-10	Minimal dimensions	Polygon			Area of protrusion	No	Target area >x map mm^2		
EuroSDR-1-11	Shape	Any			General shape	Yes	Target shape should be similar to initial shape		
EuroSDR-1-12	Shape	Any		1:n Relation (amalgamation)	General shape	Yes	Target shape should be similar to initial shape		
EuroSDR-1-13	Shape	Polygon		Initial value of angle = 90° (tolerance = ±x°)	Squareness	Yes	Target angles = 90°		
EuroSDR-1-14	Shape	Polygon		Initially high concavity	Concavity	Yes	Target shape remains concave		
EuroSDR-1-15	Shape	Polygon			Elongation	Yes	Target elongation = initial elongation ±x%		
EuroSDR-1-16	Topology	Line and polygon		Initially, no self-intersection	Intersection	Yes	No self-intersection must be created		
EuroSDR-1-17	Topology	Line and Polygon			Coalescence	No	Coalescence must be avoided		
EuroSDR-1-18	Orientation	Any			General orientation	Yes	Target orientation=initial orientation ± x%		
EuroSDR-1-19	Position	Any			Positional accuracy	Yes	Target absolute position = initial absolute position ± x map mm		
EuroSDR-1-20	Model generalization	Any			Class	Yes	Target class = initial class		
EuroSDR-1-21	Model generalization	Any			Symbolization value	Yes	Target symbolization value = initial symbolization value		

Appendix B. Appendix Harmonized constraints on two objects

GENERIC-Constraint ID	Constraint type	Geometry type combination	Class 1	Condition for object in class 1 being concerned with this constraint	Class 2	Condition for object in class 2 being concerned with this constraint	Condition on both objects (in the initial data) for them to be concerned with this constraint	Constrained property	Condition depends on initial value?	Condition to be respected	Action	Importance of constraint (1–5, 1 is less important)
EuroSDR-2-1	Minimal dimensions	Any–any						Minimal distance	No	Target distance >x map mm	IF distance <x map mm THEN {action}	
EuroSDR-2-2	Minimal dimensions	Polygon–polygon					One class must be inside within another class	Minimal area	No	Target area >x map mm2		
EuroSDR-2-3	Orientation	Line/polygon–line/polygon					Objects are parallel (±x°)	Orientation	Yes	Object (class 1) must be parallel to object (class 2)		
EuroSDR-2-4	Topology/ position	Any–any						Relative position	Yes	Target relative positions = initial relative positions		
EuroSDR-2-5	Topology	Line/polygon–line/polygon					Within a single feature class	Intersection	No	No other-intersections must be created		
EuroSDR-2-6	Topology	Line–any		Object (class 1) leads to the object (class 2)				Accessibility	Yes	Target accessibility = initial accessibility		
EuroSDR-2-7	Topology	Line–any					Initially connected	Connectivity	Yes	Target connectivity = initial connectivity		
EuroSDR-2-8	Topology	Any–any		Object (class1) overlaps object (class 2)		Object (class2) is under object (class 1)		Overlapping	No	Target overlapping = initial overlapping		
EuroSDR-2-9	Topology	Any–any		Object (class 1) contains object (class 2)		Object (class2) is inside object (class 1)		Topological consistency	Yes	Target topology relations = initial topology relations		
EuroSDR-2-10	Topology	Line/polygon–line/polygon					Minimal distance <x map mm and objects are parallel ±x°	Adjacency	Yes	Target objects must be adjacent		
EuroSDR-2-11	Topology	Line/polygon–line/polygon					Objects are topologically adjacent (sharing an edge)	Adjacency	Yes	Target topology relation = initial topology relation		

Appendix C. Appendix Harmonized constraints for group of objects

GENERIC-Constraint ID	Constraint type	Geometry type	Class	Kind of group	Kind of objects of the initial data composing the group	Condition (in the initial data) for group being concerned with this constraint	Constrained property	Condition depends on initial value?	Condition to be respected (do not forget the units)	Action	Importance of constraint (1–5, 1 is less important)
EuroSDR-3-1	Minimal dimensions	Any		Any	Any		Minimal distance and minimal area	No	Distance between objects >x map mm AND area of each object >x map mm2	IF distance <x map mm AND area <map mm2 THEN {action}	
EuroSDR-3-2	Minimal dimensions	Any		Any	Any		Minimal distance	No	Distance between objects >x map mm	IF distance <x map mm THEN {action}	
EuroSDR-3-3	Orientation	Point/polygon		Alignments			Alignment orientation	Yes	Target orientation should be similar to initial orientation		
EuroSDR-3-4	Topology	Line and polygon		Any	Any		Intersection	No	No other-intersections must be created		
EuroSDR-3-5	Topology	Line and polygon		Any	Any		Connectivity	Yes	Connectivity must remain		
EuroSDR-3-6	Shape	Any					Shape	Yes	Target shape should be similar to initial shape		
EuroSDR-3-7	Shape	Polygon		Building alignment	Buildings aligned		Spatial distribution	Yes	Target distribution should be similar to initial distribution		
EuroSDR-3-8	Shape	Polygon		Urban blocks	Buildings surrounded by minimal cycle of roads (in urban areas)		Spatial distribution	Yes	Target distribution should be similar to initial distribution		
EuroSDR-3-9	Shape	Line	Contour lines	Relief form	Contour lines that compose a relief form (e.g., riff, valley)		Spatial distribution of contour lines	Yes	Target distribution of contour lines should preserve the relief form		
EuroSDR-3-10	Shape	Polygon				Object inter-distance <x map mm	Shape	Yes	The shape of derived group of objects should be similar to the shape of the initial group		
EuroSDR-3-11	Shape	Point/polygon		Alignments			Alignment	Yes	Alignment should be kept		
EuroSDR-3-12	Distribution/statistics	Polygon		Urban blocks	Buildings surrounded by minimal cycle of roads (in urban areas)		Distribution of characteristics of buildings (shape, size, function…)	Yes	Target distribution should be similar to initial distribution		
EuroSDR-3-13	Distribution/statistics	Polygon		Urban blocks	Buildings surrounded by minimal cycle of roads (in urban areas)		Density of buildings (black/white ratio)	Yes	Target density should be equal to initial density ±x%		

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