Automated geospatial data filter for the generation of optimal geographic information: concept and implementation

Hartmut Asche*, Silvija Stankute*

* University of Potsdam, Geoinformation Research Group, Department of Geography, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany

Abstract. Geospatial information is gaining increasing importance as a valuable economic resource in the industry. This has triggered a sharp rise in demand of harmonised, uniform geographic data for a given, often interregional geographical coverage. While the amount of existing geospatial data generally exceeds the ability to access, process and use this mass data, geospatial data of a particular region, scale or quality might not readily be accessible or usable. For various reasons data acquisition for a particular application purpose is not an option. This paper deals with the development, implementation and sample application of a software system for data fusion (*DaFuS*) that produces optimal geospatial data from existing vector datasets which can be customised to individual user and/or application requirements. It is shown that *DaFuS* generated datasets are superior in their geometrical and/or semantic quality to the imperfect source data making repeated data collection of identical or similar geodata for each new application unnecessary in most cases. The *DaFuS* systems contributes to reduce the heterogeneity and redundancy of geospatial data in massive geospatial databases.

Keywords: geospatial data, data fusion, data integration, vector data, homogenisation, harmonisation, optimal data quality

1. Introduction

Geospatial information is gaining increasing importance as a valuable economic resource in the industry. The result is a sharp rise in demand of a broad range of geospatial data for a variety of scales and applications. In particular demand are harmonised, uniform data for a given, often interregional geographical coverage. By now the amount of geospatial data vastly exceeds the ability to access, process and use this mass data in a meaningful way. Hence geospatial data of a particular region, scale or quality might be available but not accessible or usable for various reasons of which political restrictions and high usage charges are the most prominent.

Figure 1. Imperfect road vector datasets in a Potsdam residential area (*Tele Atlas/TomTom* [white], *Navteq* [black], *ATKIS* [grey]), superimposed on high-resolution HRSC-A image.

For this reason, geospatial data of physical as well as man-made real-world objects are frequently collected by a range of actors including state institutions, such as national mapping agencies (NMAs) and private enterprises, according to their specific application needs and areal coverage. This results in a multitude of heterogeneous, frequently redundant geospatial databases of identical geographical coverage. More precisely, it is the geometric and semantic quality of these data that is mixed, often insufficient or inaccurate (Devillers et al. 2002, Hunter et al. 2009, Onchaga et al. 2008). *Figure 1* shows the centre lines of a road network in a residential area of Potsdam (Germany). Sample vector data are taken from *Tele Atlas/TomTom*, *Navteq* and geotopographic *ATKIS* data from the mapping agency of the German federal state of Brandenburg[1]. The sample datasets are superimposed on a geo-referenced, high-resolution remote sensing image of the *HRSC-A*[2] sensor. It can be seen that the geometrical quality of identical real-world objects (in this case: roads) vary considerably in the datasets. What this brief example demonstrates is that the quality of existing geospatial datasets is frequently poor. Data are often incomplete and unreliable in their geometrical and/or semantic features and hence unfit for any targeted data use.

Effective geodata use and management, however, necessitate the harmonisation of heterogeneous geodata according to the respective application-specific data quality specifications. For that purpose a procedure is required that generates a best-fit dataset from a number of existing suboptimal datasets of identical geographical coverage, topic and scale. Such process would contribute to restrict repeated data acquisition, limit data redundancy and enhance existing data quality. In an ongoing R&D project the authors have developed and implemented an automated data fusion system *DaFuS* to produce new geospatial data from existing vector datasets (Stankute & Asche 2009, 2010, 2011). These generated datasets are superior in their geometric and/or semantic quality to the imperfect source data.

2. Concept: Automated fusion of imperfect data

In essence, the *DaFuS* concept aims to combine, i.e. fuse, available geospatial datasets from different origins into a new, user-defined target dataset. More precisely, the relevant information from two or more imperfect datasets is merged in an automated process into an improved geospatial data-

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[1] The Dutch company *Tele Atlas/TomTom* and the US company *Navteq* are among the leading providers of digital vector data and maps for vehicle navigation. Both geospatial databases are widely used in Europe not only for vehicle navigation but also for non-navigation mapping applications, such as location-based services, marketing, business GIS, etc. The *German Authorative Topographic Cartographic Information System* or *ATKIS* is a geotopographic database collectively provided by the surveying and mapping agencies of the German federal states. *ATKIS* is the geospatial reference database for Germany which is made available in a series of digital earth surface models. Vector data used in this paper originate from the Basic Digital Landscape Model (DLM) of the German federal state of Brandenburg (courtesy LGB Brandenburg).

[2] The *High Resolution Stereo Camera* or *HRSC* is a digital high-resolution multispectral stereoscopic camera originally developed for the European Mars96/Mars Express missions to map planet Mars in full colour, three dimensions and with a ground resolution of 10 and 2 m in specific areas. A modified *HRSC* version, the *HRSC-A*, has been developed for the aircraft-based acqusition of high-resolution photogrammetric imagery. Ground resolution can be up to 15 cm/pixel from 3,500 meters flight altitude. In this paper, a geo-referenced *HRSC-A* natural colour image (courtesy of DLR Berlin) has been used as a topographic reference with a ground resolution of 23 cm.

set with all available geometrical and semantic data features required for a specific use case. The resulting target dataset incorporates all selected geometrical and thematic features of the source datasets. Attributes from source data not needed in the generated target dataset for a specific application are rejected during user-defined fusion process execution. Accordingly, the principle objective of *DaFuS* is to extract, filter, harmonise and combine relevant data features from diverse source data into a single best-fit quality dataset according to user and application specifications.

Data that can be processed with the system are geographically referenced vector data of the ASCII format. The geometry of these geospatial data is represented by the geometrical primitives of point (0D), line (1D) and closed polygon (2D). Their thematic reference, however, varies considerably from, e.g. road network attributes, such as width or number of lanes or navigation capability, or land parcel attributes, such as size, ownership or use. Geospatial data acquired by providers, such as national mapping agencies or larger commercial enterprises, usually conform to defined and documented quality standards. Depending on the respective data provider geodata quality is excellent to acceptable and by and large well documented. These data can thus easily be assessed an utilised for further processing with *DaFuS*.

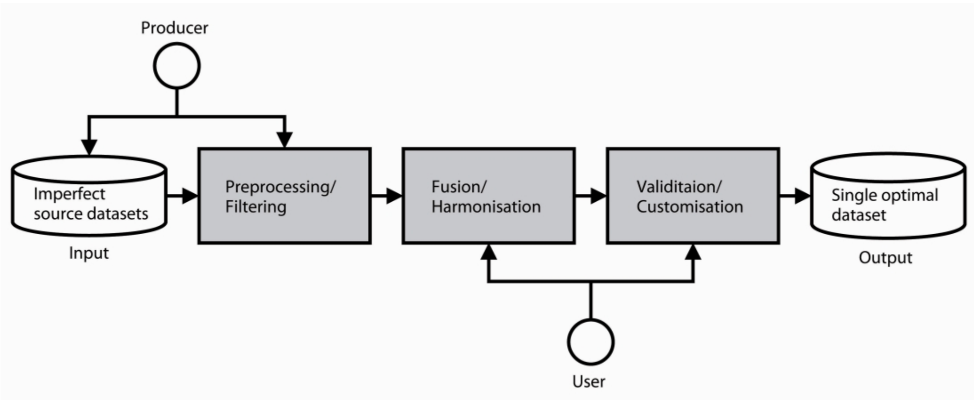

Figure 2. *DaFuS* rationale: scalable components for automated geospatial data fusion with optional user-interaction

To be able to process imperfect geospatial data from diverse sources a data fusion system has been conceptualised as a modular, scalable system of components and modules. Components selected for a data fusion task are linked in a processing pipeline (*Figure 2*). The system is generic and scalable to adapt to a range of scales, applications and user-requirements. On the one hand the fusion process can be executed in an automated workflow activated by the entry of source data into the system. On the other hand process execution is open to influence by the user who is able to determine and adjust fusion system settings through an interactive dialogue. To this end, selected filtering and harmonisation settings can be manipulated to meet specific application and/or user needs.

In the data fusion process *DaFuS* filters the imperfect geometrical and thematic attributes of the heterogeneous source datasets and extracts the required features to produce a single optimal dataset with the selected best-fit data features. Its built-in data harmonisation and fusion processes allow for selection, elimination and/or substitution of unwanted source attribute features by user-specified geometric and/or semantic attributes. In short, *DaFuS* provides a user-defined data filter to generate optimal geospatial data in an automated fusion and harmonisation workflow.

3. System structure

The *DaFuS* system structure is based on the princple of generic, modular, scalable software. Its components include (a) geospatial databases or data sources, (b) data fusion back end (operator/administrator), (c) data fusion front end (user) and (d) components and modules. The latter three constitute the system framework (*Figure 3*). Components implemented at present are: pre-processing/filtering, fusion/harmonisation, validation/customisation and output. Modules include geodata input, geodata output, geodata filter and geodata management. Core modules are: data viewer module for data output including standard data interfaces, geodata filter with context-sensitive search and filtering functions and geodata administration with system functionalities for the management of heterogeneous geospatial sources and databases. The modular system structure allows for a simple adaptation to a range of individual application- and/or user-specific requirements.

At the core of this modular, scalable system is a set of data fusion algorithms that perform the operations mentioned above. Examples of the algorithms developed for the *DaFuS* system are given and discussed in Stankute & Asche (2009, 2010, 2011). Specific subsets of the algorithms form the basis of the components and modules that constitute the *DaFuS* system. Automated execution of the data fusion tasks requires a minimum number of algorithms processed sequentially. In the system structure this mandatory sequence is mirrored in a fusion pipeline in which the corresponding components and modules are arranged. This component chain can be scaled, i.e. extended by additional components and modules, to adapt to the relevant application specifications.

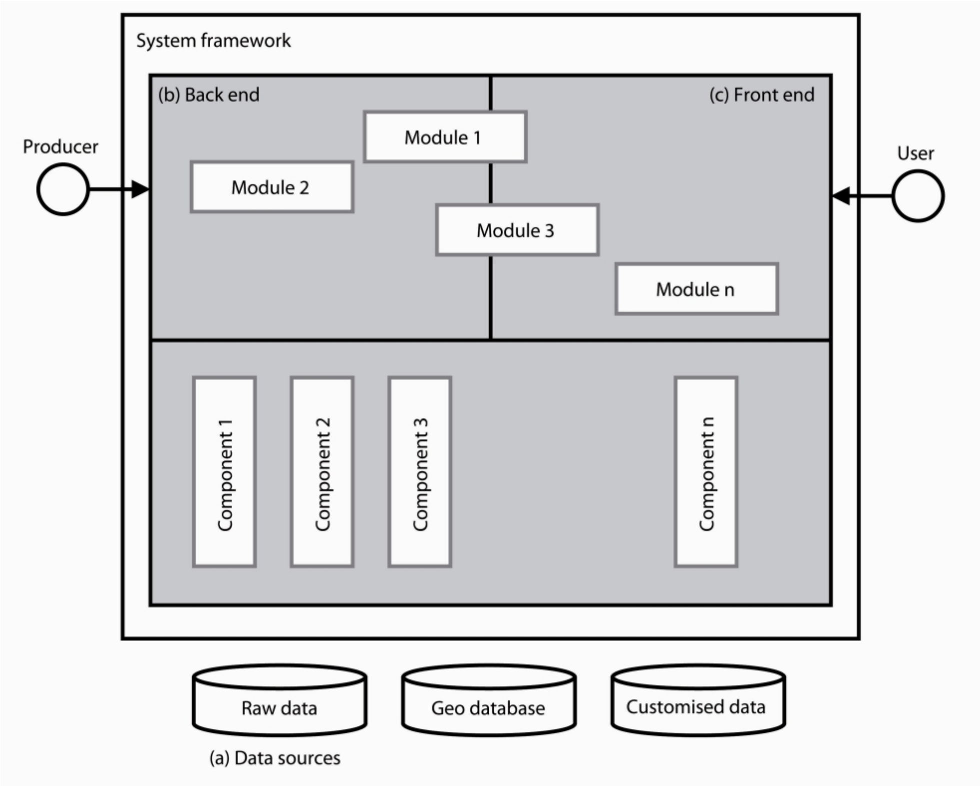

Figure 3. *DaFuS* system architecture: generic, modular framework (a) data sources, (b) system back end (producer), (c) system front end (user), components and modules.

The data fusion algorithms were implemented in the object-oriented, procedural cross-platform Perl programming language[3]. This open-source software environment has been chosen as the programming basis because of its high degree of portability. Perl runs on a broad range of platforms including portable computers and mainframes, and operating systems in-

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[3] *Perl* is a free, platform-independent, highly capable, feature-rich programming language with more than two decades of development. The current version *Perl 5* is particularly suitable for rapid prototyping as well as large scale development projects. It is widely used in web applications and practical computer science, i.a. bioinformatics or geoinformation science.

cluding Windows and UNIX derivatives. This makes it possible to run the data fusion algorithms implemented in *DaFuS* on servers and clusters without any problems. This property is essential when it comes to processing large volume input datasets - a frequent *DaFuS* use case. Perl is particularly suitable for the processing and/or manipulation of large ASCII datasets. Since *DaFuS* primarily processes ASCII files this is a relevant feature in system development. As an open-source software Perl is easily extendible with a vast range of open-source modules which facilitate scalability and adaptation of *DaFuS* to diverse data fusion application tasks.

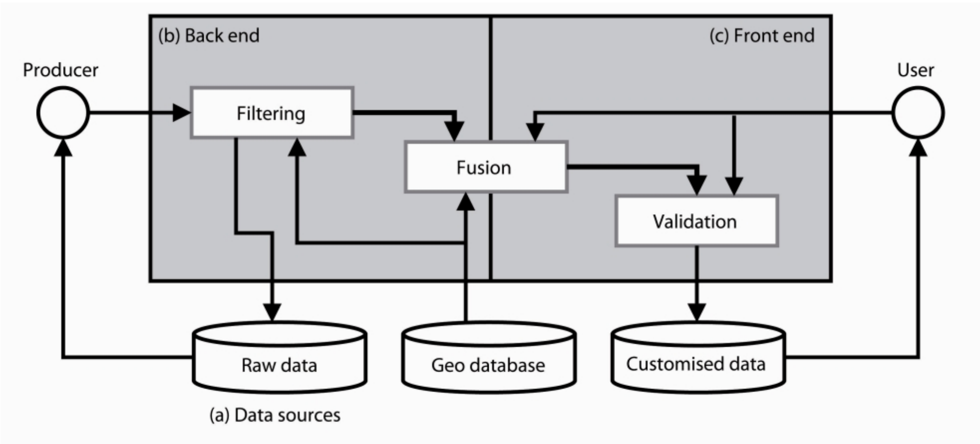

Figure 4. *DaFuS* fusion pipeline: processes and process flow overview.

4. Fusion pipeline: generic component system

Implementation of the DaFuS concept is based on a generic, modular component architecture. Presenting DaFuS consists of three components which are sequentially linked in a fusion pipeline: preprocessing/filtering, fusion/harmonisation, and validation component. Each component is composed of a set of modules (*Figure 4*):

- *Preprocessing/filtering component*: at present, this component includes input modules for Tele Atlas/TomTom, Navteq, ATKIS vector data.
- *Fusion/harmonisation component*: this component executes the fusion of two or more different preprocessed datasets into a single optimal target dataset.
- *Validation/customisation component*: this component assesses the quality of the merged dataset according to user or application specifications.

The above components are integrated into a comprehensive data fusion pipeline which implements the automated processing process into a sequential workflow. This ensures user-defined optimisation of imperfect source data. Because of its modular structure each component can be specialised or enhanced in its functional range. The principle components of *DaFuS* are assigned the following tasks:

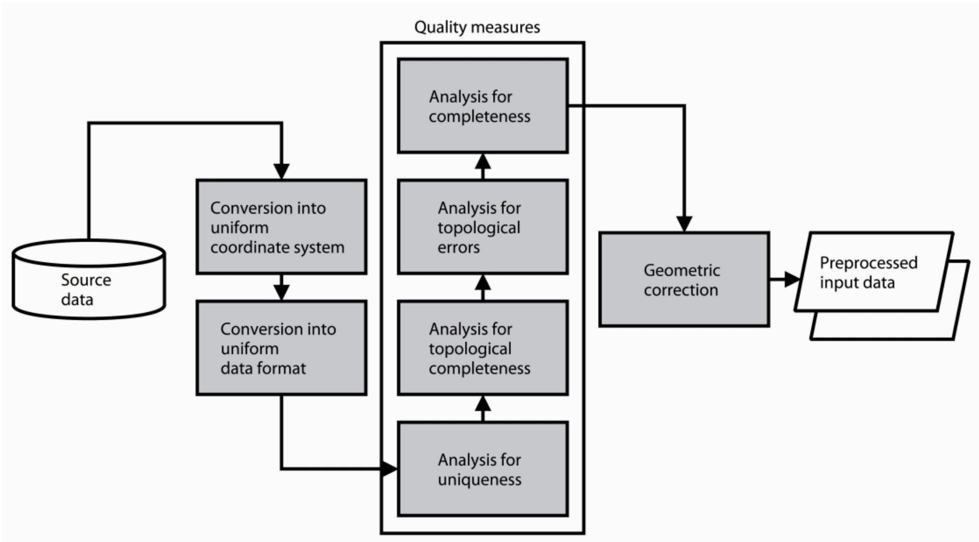

Figure 5. *DaFuS* filtering component: processes and process flows.

Data input/filtering The initial data fusion component assesses and preprocesses heterogeneous datasets from diverse data sources, such as *Tele Atlas/TomTom*, *Navteq*, or *ATKIS* data, for their geometrical and semantic feature quality (Figure 5). All input data processed in *DaFuS* are required to be vector data. Vector data represent real-world objects as geometrical primitives, i.e. points, lines or polygons. Lines consist of sequential points, closed polygons of line sequences with identical start and end points. The geometry of each point is defined by a pair of unique coordinates (x/y) of a selected geographical reference system. Hence only one point can occur at any given position. In a first step each source dataset is therefore transformed into a uniform coordinate system. In a second step the input data are converted into a uniform data format. In a third step, the uniqueness and completeness of the preprocessed input data is verified. Uniqueness denotes that one geospatial object can be represented by one object in a dataset only. Completeness requires all known semantic relations to be explicitly included in that particular dataset (Stankute & Asche 2009). Geometrical correctness as well as thematic completeness are used to compute a quality measure defining the quality of the available input data. Merging of heterogeneous geospatial data frequently requires geometrical corrections which include the eradication of duplicate geometry. The result is a set of preprocessed source data to be used as input data for the subsequent fusion/harmonisation component.

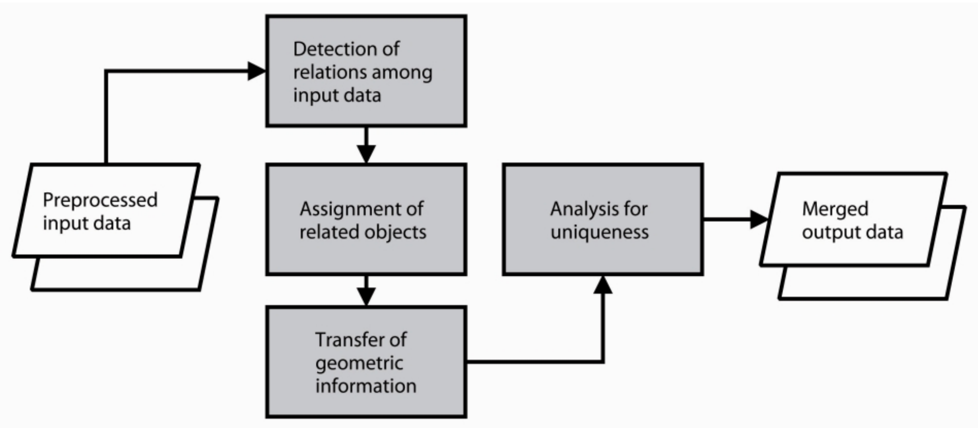

Figure 6. *DaFuS* fusion component: processes and process flows.

Data fusion/harmonisation This central *DaFuS* component executes the merging process of the preprocessed input data (*Figure 6*). In this way a single optimal geospatial dataset is generated by transmission and augmentation of attribute features from *n* input datasets. Fusion algorithms developed in *DaFuS* for each geometry primitive (point, lines, polygons) are based on direct comparison of coordinates. A more detailed discussion of the respective direct coordinate comparison (*DCC*) algorithms for linear objects (Stankute & Asche 2009, 2011) and simple polygons (Stankute & Asche 2010) can be found in earlier works. Recently, the algorithms have been extended to cope with more complex geometries. It has been mentioned that source data need to have an identical coordinate system and data format. Accordingly, each geospatial object is represented by a single geometry. In a first step, relations between objects of the various input datasets and the corresponding real-world object are established on the basis of coordinate pairs. This is the prerequisite to transfer, in a second step, the user-selected thematic features from the preprocessed data to the user-defined target dataset. The result of this cross-referencing is, (a) an extension of the feature attribute table and (b) the generation of new geometrical features of the target dataset.

The minimum input requirement for the fusion component is two datasets one of which is determined as the target dataset, either by the user or the fusion component. In the latter case the system provides the user with information about the quality of the input data and, based on the quality assessment, suggests the input dataset to be used as the target dataset in the fusion process. On the basis of the fusion information provided by *DaFuS* the user may either apply the proposed target dataset generated by the fusion component or decide which data to expand outside of *DaFuS*. In the context of *DaFuS*, user-defined enrichment of a user-selected target dataset with features from available source data is called an extension of the record. User-defined generation of a new dataset and inclusion of user-selected features from available input data is termed data filtering. In any case the result is a single merged geospatial dataset to be used as input data for the subsequent validation component.

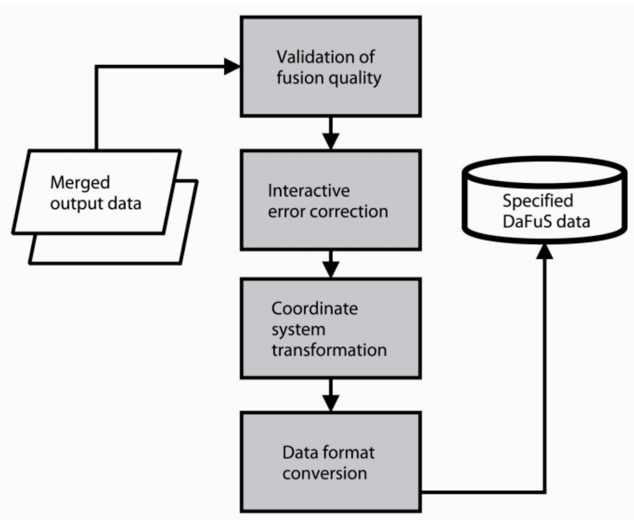

Figure 7. *DaFuS* validation component: processes and process flows.

Validation/Customisation This final component assesses and validates the geometrical and semantic quality of the single merged geospatial dataset generated in the preceeding fusion component (*Figure 7*). In a first step the quality of the data fusion process is calculated and evaluated. Once this is done possible errors detected in the merged data can be corrected manually in an interactive dialogue. Informal testing with various input data has shown that less than five percent of linear objects and about ten to fifteen percent of polygonal objects may require an adjustment. The result is a validated single optimal geospatial target dataset. In an optional step this dataset may be subjected to further modification at the user's request. If desired the dataset may be transformed into different user-selected coordinate systems (e.g. UTM, Geographic coordinate system) or data formats (e.g. SVG, CSV, SHP). In this case the end result is a single optimal geospatial dataset customised to the individual user's requirements or application needs.

5. DaFuS at work

To demonstrate how the *DaFuS* system works in its present form of implementation the following typical data fusion application are presented as an example. in a first use case we consider an application which requires a geographically-referenced, navigable road dataset with optimal geometrical and semantic data features. To avoid time and cost-consuming data acquisition *DaFuS* is employed to produce this target dataset from three available linear datasets, namely (a) *ATKIS*, (b) *Tele Atlas/TomTom*, (c) *Open Street Map (OSM)*[4] road data. A brief initial data assessment reveals that these datasets differ in their geometrical completeness, thematic coverage and topicality (*Figure 8*). Accordingly, the best-fitting data attributes are extracted from two imperfect datasets and transferred to the third dataset considered to be best suited for the application.

In the fusion process the target dataset is modified to eventually represent the single optimal linear dataset required for the application. First, the geometric and semantic data quality of the source data is analysed in the filtering component. It is found that the source dataset (a) provides the most complete line geometry. In contrast, dataset (b) contains incomplete geometrical features but provides all necessary routing attributes. Dataset (c) includes relevant thematic features not present in datasets (a, b). Employing the *DaFuS* system, a single, geometrically and thematically correct, navigable target dataset is generated by inputting the source datasets into the

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[4] *Open Street Map* or *OSM* is a wiki-inspired collaborative project started in 2004 to create free editable geographic data and mapping for everyone to use and share. Geospatial data of the fast growing *OSM* database are primarily collected by a multitude of contributors using portable GPS devices and notepads. Depending on the activities of contributors geographical coverage and level of detail vary globally as well as regionally. Germany is densely covered with *OSM* data which are currently used by around 20 million users. Decisive driving factors for the establishment and growth of *OSM* have been, on the one hand, various restrictions on the availability of geospatial data, restrictive rights of use or high purchase or usage costs of national or commercial geospatial data, such as *ATKIS* and *Tele Atlas/TomTom* or *Navteq,* and, on the other hand, the availability of inexpensive GPS devices.

preprocessing/filtering component. This component assesses the data quality with the above results. Based on the weighting of the application requirements it then selects dataset (a) as the target dataset to be optimised with the geometric attributes of dataset (b).

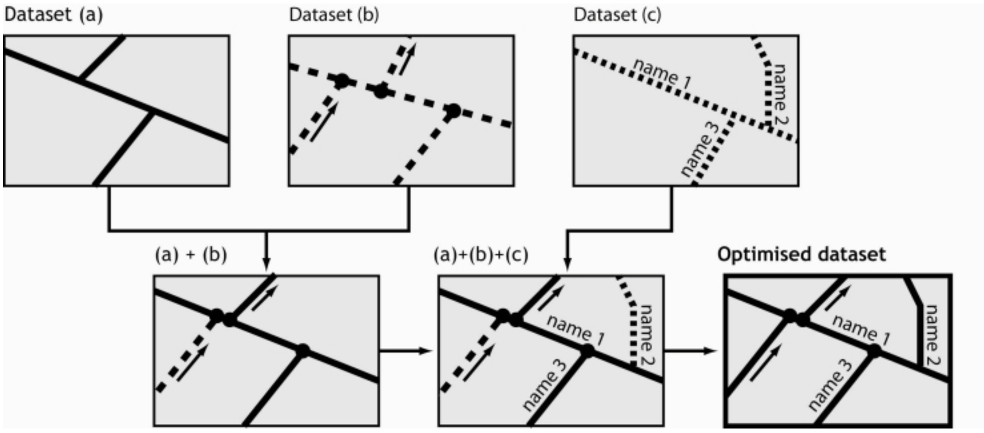

Figure 8. *DaFuS* use case (i): fusion of linear data. (a+b) fusion of geometrical attributes, ([a+b]+c) fusion of thematic attributes.

From input datasets (a,b) the fusion component generates the fused dataset (ab). Because of different data acquisition rules and methods used in the generation of datasets (a) and (b) the geometric attributes from both datasets vary and produce topological inconsistencies between the two source geometries. To fix this problem, the relevant geometrical features of dataset (b) are snapped to the geometry of dataset (a). As a consequence, the resulting dataset (ab) contains a limited number of new, inserted geometry attributes which lack the required routing features. In addition to the geometric completeness of the target dataset the application requires specific thematic information which is included in dataset (c). By splitting the line geometries of the geometrically extended target dataset (ab) the semantic features needed are transferred to the respective line segments. As a result, the attribute table of the specified (final) dataset (abc) is completed.

The above use case demonstrates how linear data are fused with *DaFuS* in an automated process. The resulting single optimal dataset incorporates the best features of each source dataset according to the application specifications. Linear data fusion can be considered the standard application of *DaFuS*. Data fusion cannot only be applied to simple linear networks, such as road networks, but also to more complex real-world objects, such as roundabouts, as has been shown in Stankute & Asche (2011).

Another frequent application of *DaFuS* is the optimisation of imperfect polygonal geodata. Heterogeneous polygonal data are fused in a step-by-step procedure similar to that of linear data: filtering/preprocessing of the input datasets is followed by referencing of objects and fusion of polygonal datasets. In contrast to linear objects polygons are more complex structures than lines. Hence the complexity algorithms necessary for the generation of a single optimised dataset differ considerably from those of linear data.

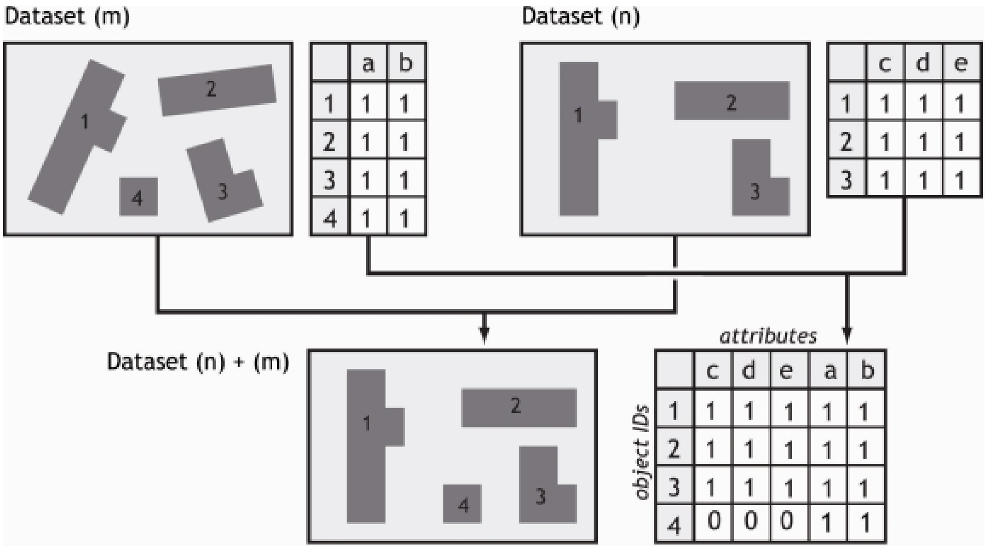

Figure 9. *DaFuS* use case (ii): fusion of polygonal data. Fusion of geometrical and thematic attributes.

To illustrate the fusion of polygonal data we consider an identical set of buildings in two geospatial datasets (m, n) (*Figure 9*). It can be seen that both polygons differ in their geometry features as well as in their thematic features. Dataset (m) is designated the source dataset. This dataset consists of four elements each of which is defined by a specific ID corresponding to the geometrical and thematic information. The task is to transfer the geometric elements of source dataset (m) to target dataset (n) in which they are missing. A complementary option would be to transfer the lacking semantic features. This operation would complete the semantic information of the target dataset without affecting its geometrical features (creation of two new columns a, b in the attribute table).

To be able to transfer the geometrical and, where appropriate, the semantic information it is essential to assign the objects of the different input datasets (Stankute & Asche 2009). Irrespective of the object type of the respective input dataset assignment of objects is mandatory to proceed with the data fusion process. To assign polygonal objects the characteristic features of all polygons under investigation have to be determined (Stankute & Asche 2010). Relevant features include shape, (e.g. concave, convex), area, perimeter, dimension as well as the polygon bounding box. In a first step each feature mentioned is calculated for each polygon of each input dataset. In a second step corresponding polygons are detected in each of the two input datasets by means of search algorithms developed for that purpose. When two polygons are found to be identical or differ insignificantly – maximum deviation of values is specified by the software following the examination of the input datasets - the polygons identified in both input datasets are defined as a pair. The subsequent transfer of semantic information is realised in pairs.

In our example we focus on the geometrical completeness of the target dataset. In this case the attribute table is expanded by additional lines (e.g. Stankute & Asche 2009) containing the thematic features of the geometrical objects transferred from dataset (m). The interim result is the extension of dataset (n) with fused geometry but unmodified thematic attributes.

The transfer of geometric as well as the semantic attributes results in a target dataset with optimised geometric and thematic information compared to the respective source datasets. It can be seen and has to be accepted by the user that the fused semantic information cannot be complete for the newly added geometrical objects. In this particular case additional thematic attributes (*a, b*) are created for objects (*ID1, ID2, ID3, ID4*). Object (*ID4*), however, does not have thematic attribute values of the attributes (*c, d, e*).

6. Conclusion

This article presents a data harmonisation concept to generate an optimal geospatial dataset with optimal geometrical and/or semantic features from a variety of source datasets in an automated data fusion process. Based on the data mining techniques of merging and harmonisation a single maximum quality vector dataset is produced by fusing the imperfect geometrical and/or thematic attributes of the diverse source datasets in an automated or user-defined workflow. This innovative fusion concept has been implemented in the generic *DaFuS* software system. Due to its modular, scalable nature the system can be adjusted to the requirements of the data to be processed and/or the relevant application specifications. Using popular geospatial vector datasets (from, i.a., commercial *Tele Atlas/TomTom* and *Navteq* databases or the national *ATKIS* database of the German mapping agencies) as input data, it has been demonstrated in test runs that single optimal geospatial data can in fact be generated from existing suboptimal datasets.

Figure 10. Fused optimal road vector dataset in a Potsdam residential area, superimposed on high-resolution HRSC-A image.

Figure 10 shows a fused road dataset with optimal geometric quality generated from the source datasets depicted in *Figure 1*. Comparing the fused dataset with the underlying geo-referenced HRSC image demonstrates that the optimised geometric quality clearly exceeds the quality of each single source dataset. In the same way the semantic quality of the target dataset can be improved.

Based on a quality analysis of the fused optimal datasets - including the comparison with newly acquired geospatial data of identical kind and geospatial coverage - it can be concluded that repeated data collection of identical or similar geodata for each new application is unnecessary in most cases. *DaFuS* thus contributes to reduce the heterogeneity and redundancy of geospatial data in massive geospatial databases[5]. Due to its modular structure and scalability the system supports, at the same time, the efficient and meaningful use of geographically-related mass data. In this way *DaFuS* helps to promote cost-effective geospatial data management by facilitating the multiple re-use of existing geospatial datasets that can be customised to individual user and/or application requirements.

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[5] *DaFuS* services are offered by the recently founded mapxtek enterprise (www.mapxtek.de).

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