Planning Agricultural Core Road Networks Based on a Digital Twin of the Cultivated Landscape

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Abstract: An appropriate and functional transportation network forms an essential basis for the competitiveness of agricultural and forestry enterprises as well as for the preservation of liveable, rural areas. Through structural changes in the field of agriculture, which become obvious e. g. by the increasing size of farms and agricultural machinery, the demands on the existing agricultural road network have changed significantly. Machines have become significantly heavier, larger and faster and due to increasing farm sizes, trans-regional transportation becomes more and more important. Considering these changed requirements, in numerous Federal States of Germany initiatives for designing core transportation networks have been launched. The goal of these initiatives is to design core road networks as needs-based, multifunctional path systems across regions. The core road networks consist of existing roads with a high relevance for agricultural transportation, which will be modernized to meet current and future needs of agriculture. Identifying these roads is a challenging task for planners. In this paper, we present digital methods for supporting planners in designing agricultural core road networks. These methods are based on a Digital Twin of the cultivated landscape. One of the core concepts of the Digital Twin is the coupling of a comprehensive, spatiotemporal information model of the cultivated landscape with complex analytical methods. Besides monitoring the current state of the agricultural landscape, the concept can also be used to assess the impact of design proposals in various aspects. This article describes the new digital methods and their application in a real planning process. Furthermore, it discusses the relation of the Digital Twin concept with the geodesign paradigm.

Keywords: Digital Twin, digital landscape model, transportation in agriculture, road network planning, geodesign

1 Introduction

A functioning and needs-based road network is essential to sustain the competitiveness of agricultural and forestry enterprises as well as for the preservation of liveable rural areas. In the figurative sense, the road systems correspond to the 'vascular system of the rural area' (Secretary of State Dr. Onko Aeikens, 2017). Structural changes in agriculture, like the increasing size of farms, have also changed the demands on the existing agricultural transportation infrastructure. With the increasing importance of inter-organizational management and expansion of farm sizes in many parts of Germany, trans-regional transports are becoming more and more important (DWA 2016). In many cases, increasing farm-field transport distances can be observed (DWA 2016, GUTBERLET 2012, SOBOTH 2012). So far, however, comprehensive studies on transport distances in agriculture have been missing.

As a result of the changed conditions, the agricultural machinery and vehicles have become significantly more powerful and thus often larger, heavier, and faster (GUTBERLET 2012). In many places, rural transport infrastructure is already no longer able to meet today's demands of agriculture (SOBOTH 2012). To counteract this fact, initiatives have been launched in numerous Federal States of Germany to reorganize the agricultural road system as needed – as in Bavaria with the 'initiative rural core road network' (BRUNNER 2014). The aim of this

Journal of Digital Landscape Architecture, 4-2019, pp. 316-327. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-663-5, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537663034.

initiative is to build a multifunctional, integrated, supraregional and thinned core road network that meets both the requirements of agriculture and society (BROMMA 2014). On the one hand, this core road system should improve the accessibility of agricultural parcels and on the other hand contribute to the steering of agricultural transport (DWA 2016). Since the needs- and future-oriented transformation of the rural road system is associated with very high costs, both spatial and temporal priorities for modernizing the road network have to be defined. The agricultural and forestry road network in Bavaria has a total length of around 300,000 km. From this road network segments have to be selected, which are considered as components of a rural core road network. As possible criteria for the selection of core paths, literature mentions not only the maintenance status and the function of individual paths, but also the agricultural area that is connected via individual segments (AKADEMIE FÜR DIE LÄNDLICHEN RÄUME SCHLESWIG-HOLSTEIN E. V. et al. 2008, BERTLING et al. 2015). The acquisition of such information is usually associated with enormous human resources and not always completely objective (AKADEMIE FÜR DIE LÄNDLICHEN RÄUME SCHLESWIG-HOLSTEIN E. V. et al. 2008). In addition, the exclusive focus on the planning region disregards the trans-regional importance of individual paths (BERTLING et al. 2015). In this context, we developed a digital method for the state-wide monitoring of real farm-field transportation paths. On the one hand, the tool is designed to perform a state-wide analysis of all farm-field transportation relationships. On the other hand, it provides a very high level of detail and estimation quality at the scale of individual objects or relations. The key research questions are:

- How to design an information model in order to use it as a spatiotemporal Digital Twin of the cultivated landscape?
- What concepts are needed to use the Digital Twin for the fusion of interdisciplinary information?
- How can algorithms be used to derive realistic farm-field transportation paths taking into account the existing transport network, the location of farms, and their agricultural parcels?
- How can the traffic significance of individual path segments within the agricultural road system be quantified?
- How can the developed concepts for the monitoring of the current state also be used to evaluate possible states of the future in order support a geodesign process?

The digital methods described in this paper are based on a Digital Twin of the cultivated landscape, which is developed in the research project LandModel^{TUM}.

The following section first outlines the need for modelling the cultural landscape in the form of a spatiotemporal Digital Twin. The subsequent sections describe the methods for estimating farm-field transportation paths and the derivation of an indicator for quantifying the traffic significance of individual segments within the road network. The results section describes the application of the methods in a real planning project and the results of a quality assessment of the method. The last section discusses the results and gives a summary and outlook.

2 Towards a Digital Twin of the Cultivated Landscape

In general, a Digital Twin is a digital representation of a physical object, such as an aircraft engine or a production plant. The Digital Twin is kept up to date throughout the entire life cycle of the physical object, with the aim of synchronizing the state and behaviour of the

Digital Twin with the state and behaviour of its physical counterpart. The Digital Twin concept promises to optimize the development, operation and maintenance of products. (e. g. GLAESGEN et al. 2012, DATTA 2017). In contrast to industry, where all the information about a specific product is organized and bundled by one stakeholder, the information about real world objects of the agricultural landscape like parcels, roads, farms and so on are distributed across several organizations and stakeholders. Creating and maintaining a Digital Twin therefore first of all means information integration. Due to the distributed and heterogeneous nature of the information, creating the Digital Twin of the cultivated landscape is challenging, both from a technical and organizational perspective. The scope and information content of the Digital Twin goes beyond traditional Digital Landscape Models: Besides topographic objects, it also covers specific agricultural objects (like agricultural parcels, their crop rotation, farms) and semantically enriches topographic objects with agricultural information (like the cultivated area connected to a specific road segment). In addition, the Digital Twin represents temporal relations between objects and the evolution of objects over time, and object identifiers are kept stable throughout the life time of the corresponding real-world objects. Furthermore, the information model of the Digital Twin provides a modelling framework, that allows the semantic extension of existing objects and adding additional object types in order to comprehensively model the state of the real world. These additional capabilities of the Digital Twin allow for a good integration with the geodesign paradigm (see section 5).

The information model of the Digital Twin is formally described as a UML class and package diagram based on standards of the ISO 19100 family (especially ISO 19107, ISO 19108, ISO 19109) consisting of a core module and thematic modules e. g. for agricultural parcels, land use, transportation, land consolidation, statistical aggregation units, etc. These modules are modeled as UML packages within the information model (figure 1). The information model currently contains 19 thematic classes and 8 additional classes e. g. for modeling temporal aspects or transitions between objects over time. The number of attributes modeled in each thematic class ranges from 10 to 20 attributes per class.

Due to the concept of semantic enrichment, it is also possible to assign additional information to the individual objects. The direct referencing of interdisciplinary information to individual objects facilitates an integrated view of the cultivated landscape as a complex system. This information may be linked information from external information systems, real time information provided by sensors or the output of complex analytical methods.

Therefore, a fundamental concept for building up the Digital Twin of the cultivated landscape is the coupling of the comprehensive, spatiotemporal information model with complex analytical methods. These methods deal with different aspects of the cultivated landscape. Several analytical methods have already been developed in the project. In addition to the estimation of the agricultural transportation paths, described in this paper, methods for the description of the geometric characteristics of agricultural parcels as well as methods for the detection, analysis and documentation of changes of the cultivated landscape at the level of individual elements have been realized (MACHL et al. 2013, MACHL et al. 2015, MACHL et al. 2016). Most of the analytical methods are implemented using the spatial ETL software Feature Manipulation Engine (FME). All information gained in the analysis processes flow back to the affected objects, such that they are available for further interdisciplinary analyses. By creating clones of the Digital Twin, the concept can also be used to evaluate possible future states of the real world and therefore allows a close coupling of design and impact analysis according to the geodesign paradigm (cf. FLAXMAN 2010, STEINITZ 2012).

The information system is implemented using the object-relational database management system PostgreSQL (www.postgresql.org), including the extensions PostGIS (postgis.net) and pgrouting (pgrouting.org). Data integration is performed using FME. As of 31.12.2018, more than 26 million objects represent the current state of the agricultural landscape. Since the system also covers temporal aspects, due to the versioning of the objects, the information system contains significantly more objects considering time.

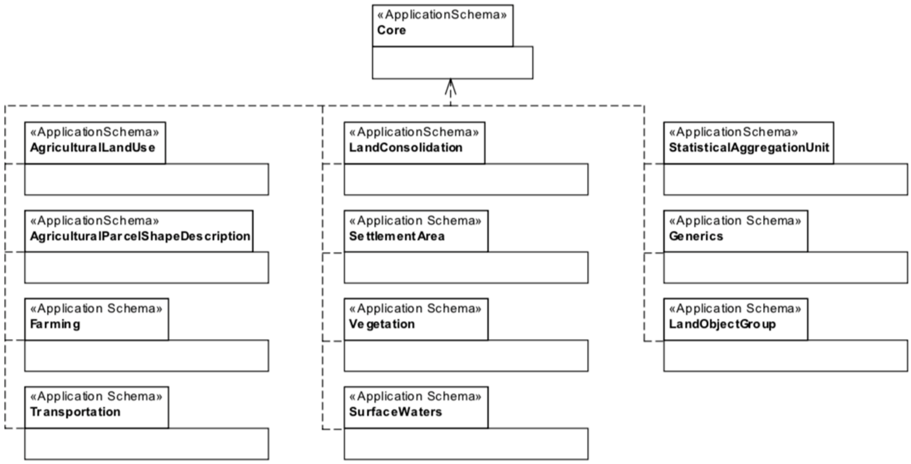


Fig. 1: UML package diagram of the aspects modeled in the information model of the LandModel^{TUM}. Details on the data model are given in MACHL et al. (2015).

3 Methods for Analyzing Transportation Flows in Agriculture

3.1 Estimating Farm-Field-Transportation Paths

The route between farm and field is one of the most important transportation relationships in agricultural transport. According to DEMMEL (2014), 75 % of the transport masses generated in agriculture can be assigned to the transport of goods between farm and the associated parcels. The method presented in this paper estimates the farm-field transportation paths mainly based on anonymized data from the European Integrated Administration and Control System (IACS), more precisely of the Land Parcel Identification System (LPIS) as a part of IACS (INAN et al. 2010), as well as on geospatial data of the official German topographical cartographic information system (ATKIS; ADV 2015). The data of the IACS provide information on the geometry of the approximately 1.8 million agricultural parcels (‘farmer blocks’ in Bavaria) as well as on the locations of the farms cultivating each parcel. The ATKIS road network forms a geometric network of lines representing all types of roads and contains a number of attributes describing the individual route segments (e. g. road type, surface material etc.). By deriving the incidence and adjacency relationships from the implicit network topology of the ATKIS path segments (identical start and end coordinates of individual segments), the path network can be transformed into a graph structure consisting of edges and nodes. This graph can be used for routing purposes. The computation of the paths between parcels and associated farms is done by minimizing the costs along the paths using the algorithm according to DIJKSTRA (1959). Different preferences for different road categories are expressed through specific weighting factors in the form of assumed driving speeds for different types of roads (figure 2). The costs for using each road segment correspond to the travel time required for passing the road segment and are determined by its length and the assumed speed for the segment type.

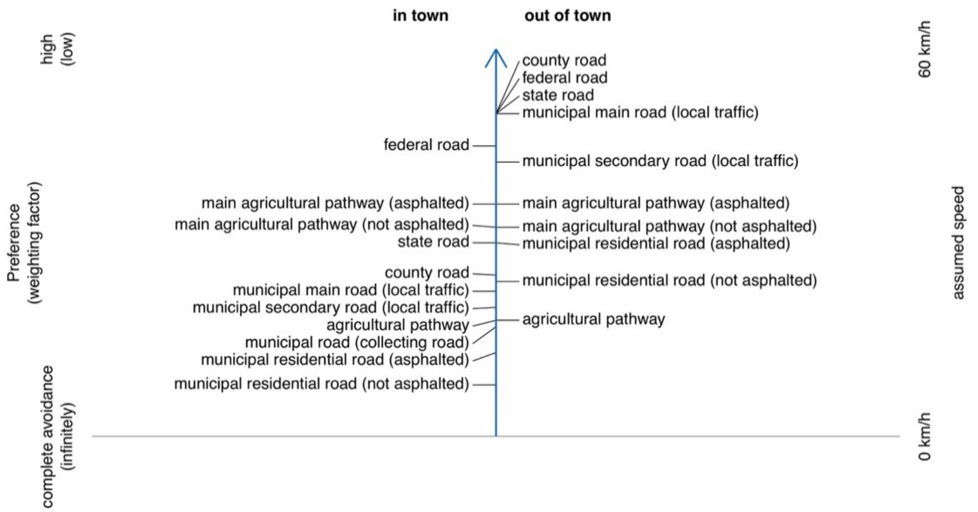
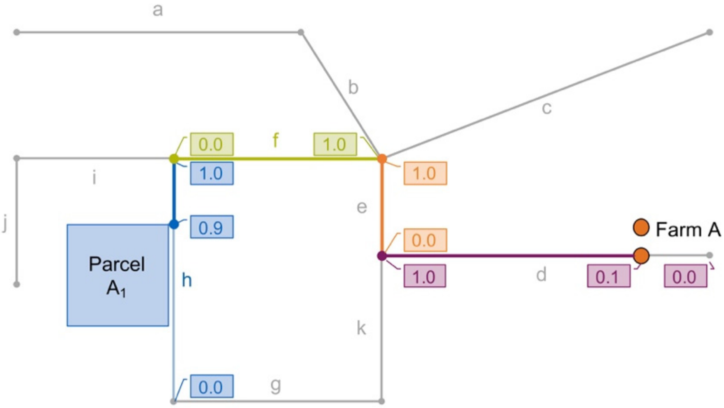


Fig. 2: Weighting factors and preferences for different road types are based on the assumed speed of a vehicle along a path segment

Farm-field paths are stored in small segments in the form of linear references to elements of the road network – the calculated paths are composed of their individual components. This method gives full access to the objects involved and their attributes. This approach allows a wide range of further investigations, e. g. analysis of the composition of individual paths or the estimation of the importance of individual components of the road network for agricultural traffic (see sections 3.2 and 4). Figure 3 illustrates the principle with an example showing the representation of the transportation path between farm A and parcel A_1. For state-wide monitoring, the 1.7 million routes between agricultural parcels and more than 102,000 farms were calculated on the basis of the data. For the year 2018 the results consist of more than 47,000,000 references to segments of the road network, farms, and agricultural parcels. The estimate covers 97 % of the farm-field transportation relationships in Bavaria. The remaining 3 % of the farm-field relationships either lacked information about the farm locations or the parcels were not connected to ATKIS road segments. Details on the results of the state-wide monitoring can be found in MACHL et al. (2016).



idFarm	idParcel	index	idSegment	$from_{rel}$	to_{rel}
A	A_1	0	d	0.1	1.0
A	A_1	1	e	0.0	1.0
A	A_1	2	f	1.0	0.0
A	A_1	3	h	1.0	0.9

Fig. 3: Segmented representation of the farm-field transportation paths in the form of linear references to the elements of the road network

3.2 From Single Paths to the Importance of Individual Segments Within the Agricultural Road Network System

As already mentioned above, the segmented representation of transport routes in the form of references to individual components allows full access to the objects involved and to their properties. This procedure allows for a detailed analysis of the path composition for individual routes and – with the knowledge of all paths – allows for an estimation of the agricultural area connected via individual segments. The procedure for deriving the connected area for a single road segment from individual farm field transportation paths is illustrated in figure 4. To derive the connected agricultural area for individual segments, the areas of the adjacent parcels are to be aggregated.

For the planning of a rural core road network, the agricultural area connected to a road segment is an important indicator for the significance of a single road segment within the road system. It provides a substantial basis for the selection of major and minor corridors of the agricultural traffic network. In addition, this indicator also provides information on the need-based dimensioning and temporal prioritization of the road construction works.

The agricultural area connected to a segment can be further discriminated by different types of crops cultivated on the area (current and historical). By defining crop-specific area-dependent and area-independent cultivation operations, it is possible to derive differentiated seasonal information on the masses flowing over individual segments. This information can be used for determining the road load. Initial research in this direction has already been carried out by GERL (2018) as part of the LandModel[TUM] project. In addition to a monitoring of a current or a future state, this information also could be used for a predictive maintenance of the roads, which is one of the key advantages of Digital Twins (c. f. DATTA 2017).

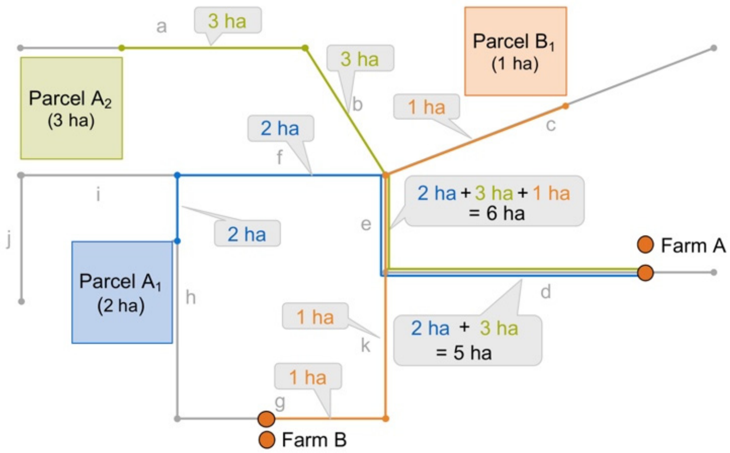


Fig. 4: Derivation of the indicator 'connected area' for road segments from single paths

4 Results

4.1 Application of the Methods in a Planning Project

In order to evaluate the potential benefits of the novel information for the design of the agricultural core road systems, for a model region the planners were provided with geospatial data of the road network enriched with information on the total agricultural area connected via single segments. This model region – called 'NES Alliance' – is located in northern Bavaria and comprises 13 municipalities with a total area of about 284 km^2. Figure 5 shows a map of the existing road network in the project area. The colour of the lines represents the road type, from large federal roads to small agricultural pathways. The line width represents the indicator 'agricultural area', which was estimated using the methods described above. Most interesting to planners are small agricultural pathways with a high indicator value, as they most likely do not fulfil the requirements of modern agricultural machinery. In addition to information on the total area connected via a single segment, the segments also carry information on other indicators like the area of the different agricultural crops and the estimated number of farmers using a segment to get to their parcels.

According to the planners, the developed approach has its strengths in providing detailed, objective and reliable information on the significance of individual route segments within the entire network of paths. This is an essential prerequisite for selecting individual segments as parts of the core road network. The results are very useful for communicating design proposals with the stakeholders. Since the Digital Twin serves as an integration platform for all kinds of information gathered and produced throughout the planning process, all stakeholders refer to the same objects, both in the real and the digital world.

Another strength of the method mentioned by the planners is its ability to estimate the trans-regional importance of an individual road segment. This could be done because the method had not only been applied to the project area, but to the entire territory of Bavaria. In addition to an analysis of the actual state, it is also possible to analyze and evaluate various planning alternatives in a virtual representation of possible future realities. Individual segments within the road network can be 'virtually upgraded' or removed from the road network and the effects of a planning scenario on the entire network can be estimated. The results can then be compared with the results of alternative scenarios and the expected effects of planning can be discussed at an early stage. This approach was already used in the 'NES-Allianz' region and used for optimizing the planning results.

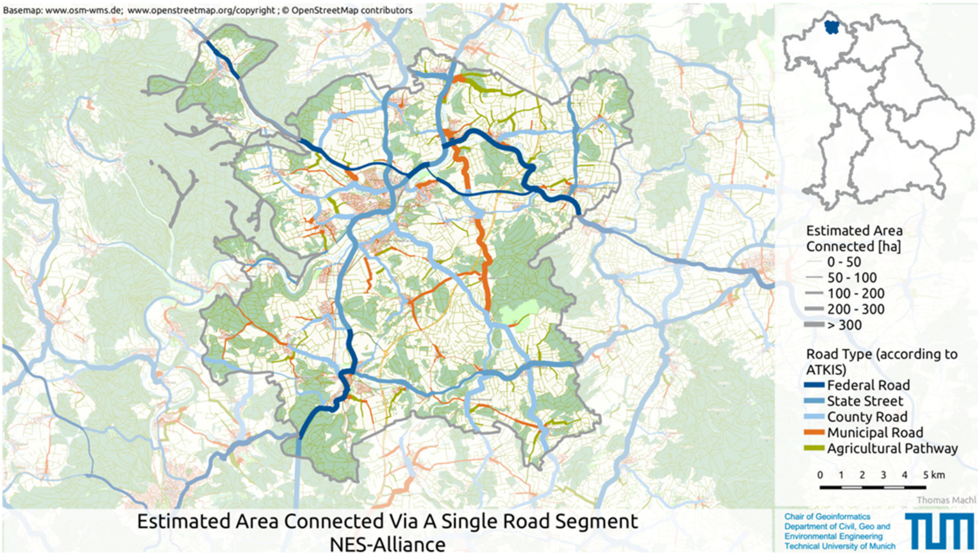


Fig. 5: Estimated area connected via a single road segment derived from farm-field transportation paths

4.2 Quality Assessment

Of course, the routes that farmers take between their farm and their parcels may deviate from our estimation. High deviations between estimated and actual routes would introduce incorrect information into the planning process. Therefore, an extensive comparison was made between actual and estimated transportation paths in order to statistically assess the estimation quality (see ASTNER 2017). In a comprehensive survey, 14 farmers from the region 'NES-Alliance' (see figure 5) were asked to compare the estimated paths with the routes they were actually taking. The study compares about 800 calculated paths with the actual routes. The evaluation of the estimation quality includes a comparison between the actual and the calculated transport distance as well as a quantification of the congruence between the actual and the estimated path. The latter was quantified using the 'Degree of Congruence' (DOC) indicator (figure 6). Any deviations were recorded.

The comparison of computed paths with actual routes showed a very good estimation quality of the developed approach both in terms of transportation distances as well as in terms of the congruence between actual and calculated paths (figure 7). For 73 % of the evaluated routes evaluated, there was a complete match between the calculated and the actually used paths. For 90 % of the calculated paths, the match was at least 76 % and for 80 % of the routes at least 81 % of the path length. Larger deviations could mostly be explained by steep inclines of roads, traffic structures not passable by agricultural vehicles (bridges, underpasses) and the avoidance of residential areas and highly frequented roads. Since the estimation of the connected agricultural area directly derives from individual paths, the very good forecasting quality of individual routes also indicates a high estimation quality of the indicator 'connected area'.

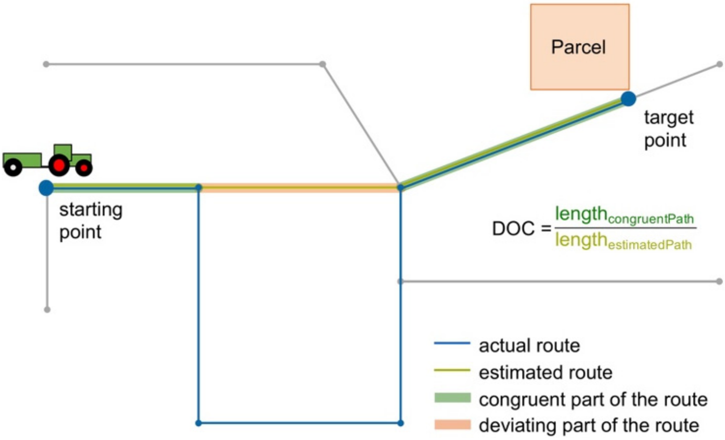


Fig. 6: Comparison between actual and estimated farm-field transportation path and quantification of congruence using the indicator 'Degree of Congruence' (DOC)

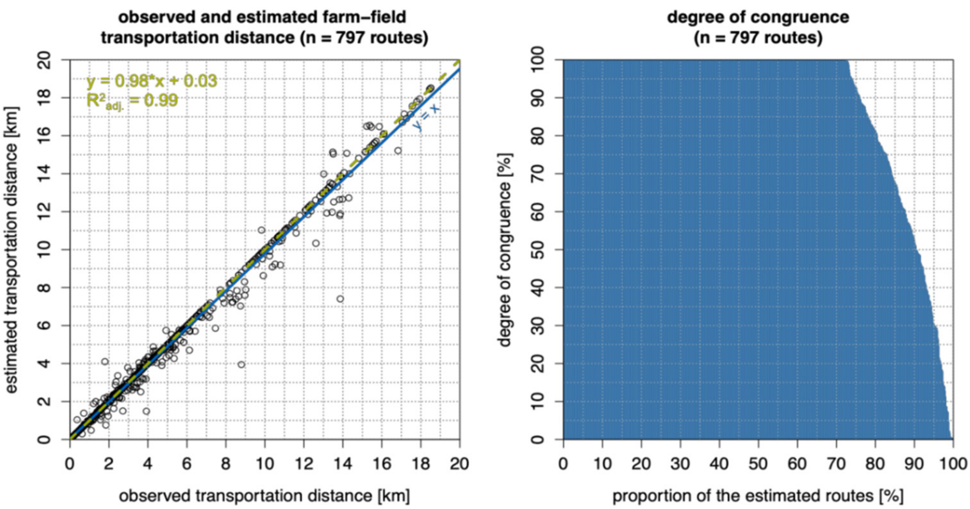


Fig. 7: Scatter plot of the observed and the estimated farm-field transportation distance (left); degree of congruence between the estimated and the observed transportation paths (right); data source: ASTNER (2017)

5 Conclusions and Outlook

The information model developed as part of the research project LandModel[TUM] is a major step towards a Digital Twin of the cultivated landscape. A basic concept of our approach is the strong coupling of the semantic data model with complex analysis methods. According to the principle of semantic enrichment, the information gained during the analysis processes flows to the relevant objects and is stored there. The information is available at the object level for further analyses as well as for a comprehensive interdisciplinary exploration of the entire system 'cultivated landscape'.

Based on this information model and its implementation in an information system, several tools have already been implemented for the analysis of various aspects of the cultivated landscape. The analytical toolbox already includes methods for detecting, documenting and analyzing spatiotemporal changes of the cultivated landscape at the level of individual objects. Furthermore, methods for a profound parametric description of the shape of agricultural parcels, methods for estimating agricultural farm-field transportation paths, and methods for analyzing the connection of agricultural parcels to the supraregional transportation network are provided. Finally, methods for estimating the area connected to single road segments as an indicator of the importance of individual path segments within the entire road system have been implemented.

The method is mainly based on geospatial data from the Integrated Administration and Control System (IACS) (position of agricultural parcels, farms and their relation) and geospatial base data from the national/federal surveying authorities (road network, georeferenced addresses). Due to the availability of identical geospatial data in all federal states of Germany, the developed methods and concepts are directly transferable to other federal states. As the member states of the EU are obliged to set up an IACS, geospatial data on agricultural land use are available in comparable form for all EU member states. Additionally, the availability of routable road networks must be checked for individual countries. Volunteered geographic information from the OpenStreetMap project may also be suitable for that purpose. A transferability of the method to other EU countries should therefore be possible.

Due to the high level of detail – the investigations are always carried out on the smallest possible geospatial unit – the methods can be used both for a state-wide monitoring as well as for local considerations. Hence the methods provide good support for a well-informed planning process and can be used for analysing possible future states. The impacts of a planning alternative can be directly estimated. However, the indicator 'connected area' is just one of many to be considered in the planning process. Other indicators derived from further analytical methods might cover, for example, economic (e. g., cost), environmental (e. g., compensation needs), or social (e. g., recreational) impacts. Initial investigations on these aspects have already been carried out in HAGSPIEL (2016), ASTNER (2018), and GAPP (2018). Integrating all these indicators into the Digital Twin by semantically enriching the objects allows for an integrated assessment of planning scenarios.

We assume, that the Digital Twin concept provides substantive benefits for the geodesign process as it contributes to the following *models* introduced by STEINITZ (2012). The Digital Twin has been designed to represent all the relevant objects of the agricultural landscape and can therefore be used to describe the current state of the landscape (*representation model*). It is possible to use the objects of the Digital Twin as input information for complex analytical methods and it is also possible to semantically enrich these objects with the results of the analyses (*process models*). Clones of the Digital Twin can be used to alter the agricultural landscape, in our example the 'virtual upgrading' of the agricultural road network (*change models*). Based on the clones, analytical methods can be used to assess the differences caused by alternating the landscape with regards to various aspects (economic, ecologic, social) (*impact models)*. The concept of cloning Digital Twins of the landscape will be a major focus of our future work.

Acknowledgements

The authors would like to thank the Bavarian Administration for Rural Development for funding the research project LandModel^{TUM}.

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