DISSERTATION / DOCTORAL THESIS

Titel der Dissertation /Title of the Doctoral Thesis

„Reconstruction of prehistoric and historic road and path networks in vegetated areas through the application of Airborne Laser Scanning“

verfasst von / submitted by

Willem Vletter, MSc

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Doktor der Philosophie (Dr.Phil.)

Wien, 2022 / Vienna 2022

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	UA 792 309
Dissertationsgebiet lt. Studienblatt / field of study as it appears on the student record sheet:	Urgeschichte und Historische Archäologie
Betreut von / Supervisor:	Univ.-Prof. Mag. Dr. Michael Doneus
Betreut von / Supervisor:	Prof. Dr. Ir. Theo Spek

Contents

Chapter 1 General Introduction

1.1 Introduction

The Dutch archaeologist Bakker already stated in 1976: "*It is a fascinating thought to travel - today - over parts of roads which have existed since the dawn of history*" (Bakker 1976). Indeed, it is not only thrilling to experience historic roads and paths nowadays but is also fascinating to realize how important these have been for historic societies. It is safe to state that historical transport, and all the aspects involved, can tell us a lot about the landscape and its use in the past. Therefore, historical road research is strongly linked to local, regional as well as national and international entities and to political, military and socio-economic systems. Indeed, transport networks represent an important means to communicate. With respect to these road connections all kinds of research questions arise about travel conditions and transport modes, migration, mobility, and mutual contacts and exchange between various cultures and societies.

Roads and paths are an inherent part of any landscape. Road networks develop through time and their investigation tells also about landscape history: They can be shaped organically by tracks of humans and animals or built in a more organised way by groups of people (e.g. Roman roads).
Terrain conditions are decisive factors for the viability of a road or path (Murietta-Flores 2010). Especially in premodern history, topography, weather and seasonality affected the state of roads considerably, and often determined if a road could be used or not. This can be seen on old maps, for example those of the province of Drenthe in the North-eastern Netherlands, where the expression *somer paßabel* along a road means that the road was only viable in the summer (see fig. 1).

Fig. 1 Detail of southeast Drenthe of the Pijnacker map of 1634. The writing “Somers paßabel“ along roads meant that these roads were viable only during the summer.

Although waterways have had their own importance as communication routes, for land routes they could form huge obstacles. Bridges and fords crossing these waterways seriously influenced the course of road networks (Baumann 1992, Brolsma 2010). The same accounts for passes in mountainous areas (Doswald 2014). Factors like territoriality and supply and demand should not be underestimated. Indeed, political and economic changes can lead to a reduction or an increase of movement along certain routes (Barisitz 2017). The use of a road and its maintenance are crucial for its condition (Bishop 2014, Gibson 2007) However, intensive use in combination with soil properties can lead to decline in viability. As a result, in some cases a new track would be created next to the old one (Denecke 2007a).

Examples of planned roads are those in the Early Modern and Modern polder landscapes in the Netherlands, which are strongly related to reclamation processes, land divisions and design principles of the project developers and their customers (Reh et al. 2007). In other areas, the economic function of roads is more related to the exchange of goods and the extraction of raw materials,like the roads made for coal extraction in the Harz mountains in Germany (Liessmann 2010). However, roads can also have a sole political motive as an expression of power, like the straight royal hunting roads built by French, English, Dutch, Danish and Swedish monarchs in the 17th and 18th centuries (Konold 2015).

A differentiation in function is also possible, like in the ancient Maya societies where different causeway-systems existed for political and economic purposes or ones for religious purposes (Chase and Chase 2001, Erickson 2009).

All these examples show that roads are strongly linked to landscapes and their history. Therefore, it is very worthwhile to investigate roads and paths in order to learn more from them about our past. It is not only useful to investigate the history of roads, but it could - or even should - be one of the main frameworks to build landscape historical research on, for instance in a landscape biographical approach (Elerie & Spek 2010, Kolen & Renes 2015). The disciplines of landscape archaeology and historical geography could considerably benefit from such an approach (Denecke 2007b, Gibson 2007). As stated before, road and path networks were necessary to shape the landscape. Water transport networks had similar importance and for some landscapes even more (Denecke 2007b). However, the focus of this dissertation lies on historical roads and paths.

1.2 Problem definition, research aim and central research question

Scientific research regarding (pre-) historic road and path networks is a field in which there is still much research to be undertaken (Guttormsen 2007). The physical, geographical, and jurisdictional knowledge of (pre-) historic roads can provide important insights into the use of past landscapes. Where roads have been abandoned in previous times, their physical remains can often still be found. Unfortunately, many of the remnants of roads have vanished or are not visible to the naked eye because of (modern) agriculture (Vletter & van Lanen 2018), building activities, and geological processes. Nevertheless, prospection techniques like aerial photography, satellite imagery and geophysical prospection can help us to detect former roads which are hidden on or below the modern ground surface.

For a long time, the application of prospection techniques in heavily vegetated or forested areas has been very problematic. This has had a negative impact on research as roads and paths tend to be better preserved in vegetated areas. Over the last decades, Airborne Laser Scanning (ALS) has changed this situation. With this remote sensing technique, it is possible to visualise on a large scale the microtopography of landscapes. Moreover, it can also be applied in heavily vegetated areas. Therefore, it is nowadays possible to conduct research on road networks on a large scale in these areas. Since the beginning of the 20th century, research has been dedicated to the use of ALS data for road and pathway detection (David et al., 2009, Štular 2011, Doneus 2013, Opitz & Cowley 2013, Sevara et al 2016, Kazimi et al 2018, Nuninger et al. 2020, Li et al 2021). This dissertation is part of that research and focuses on the application of airborne laser scanning for the reconstruction of road networks on a large scale.

The main **aim of the dissertation** is to develop a methodology for the reconstruction of road and path networks based on ALS data. Basic research will be tested in two different case-study areas with different landscape settings on an interdisciplinary basis.

The **central research question** has been: *What are the possibilities of large-scale ALS data for the reconstruction of (pre-) historic road and path networks?*

The underlying objective has been to develop a methodology to use ALS data for historical road and path research, which is applicable in different areas of Europe or even the world.

Reconstructing path networks needs to follow several basic steps: identification of paths, mapping of paths, creating a (relative) chronological model of the mapped instances, reconstructing paths in void areas, validating the results, and finally the visualisation and discussion of the results.

Based on these steps, several sub questions will have to be addressed:

- In how far can techniques for line extraction be used for a semi-automatic identification and mapping of roads and paths on ALS data?
- What factors can be applied to determine the relative chronology of road networks and how can this be visualised?
- What model based on landscape characteristics together with found networks can help us predict paths in order to complete missing parts of our path networks?
- How can the development of road and path networks over time and space be visualised? These questions will be discussed and tested in the mentioned case-study areas.

Some methodological issues have to be dealt with, beforehand. Therefore, the sub aims of this project are:

1. The development of a technique which enables the (semi) automatic extraction of roads from ALS data in forested areas and which is applicable to different landscapes.
2. To develop a methodological framework to determine the relative chronology of the roads found in the study areas.
3. Studies on predictive modelling of road and path networks based on knowledge from existing networks and the characteristics of the landscape.
4. The spatio-temporal visualization of roads networks, with a focus on their development.

1.3 State of research

There is a long tradition of road research in archaeology and other disciplines (Bakker 1976, Agrote-Espino et al, 2005, Horsten 2005, Chadwick 2007, De Laet et al., 2007, Denecke 2007, Gerking 2013, Szilagyi 2014, Köhler 2015, Rodat 2019). In most of these works, roads are investigated by using frequently applied sources like

archaeology, historical maps, field survey and historical writings. In addition, an interesting volume to mention is *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective* edited by Snead, Erickson and Darling (2009). In this book topics not often investigated regarding roads are dealt with, like song tradition for mental maps and reconstruction (Darling 2009, Snead 2009), metaphysical and symbolic meaning of words for roads (Keller 2009), the effect of climate on preservation (Ur 2009) and roads and paths as landesque capital (Erickson &Walker 2009).
Despite the mentioned long tradition, there are still considerable gaps in the knowledge regarding (pre-)historical roads and paths (Aston, 1985; Guttormsen, 2007). A lack of fundamental scientific studies is the main cause of these knowledge gaps. As a result, there is an urgent need for more extensive theoretical and methodological studies of past roads and paths (Guttormsen, 2007). Moreover, landscape managers and spatial planners could benefit from more inventory and applied studies of historical road systems.

Roads have been investigated for a long time by using historical maps, travelling guides, aerial photographs and field observation. In vegetated areas, like heathland and forests, roads are normally better preserved than in agricultural fields. This is also the starting point for the following research, in which remote sensing in particular plays an important role.

Remote sensing techniques are very suitable for road and path research because the scale of these data allow us to follow their tracks over long distances, covering whole landscapes. If we consider aerial photography, there is almost a century of experience available with regard to the archaeological interpretation of images (Wilson 2000). Perhaps the most spectacular results have been achieved in the Tavoliere of Puglia in Italy by Bradford in the 1940s (Bradford, 1956). Good results have also been obtained (Alvisi 1970) with regard to the detection of Roman roads (Alviisi 1970, Verhoeven 2009).

Although the use of satellite imagery is often expensive, it is currently being applied on projects worldwide (Argote-Espino & Chavez 2005 Carballo & Pluckhahn 2007, De Laet et al. 2007, Lertlum & Mamoru, 2009). Both aerial photography and satellite imagery are mainly utilised in open areas. However, roads and paths tend to be better preserved in wooded areas. Due to the difficult accessibility of these areas, prospection has been problematic (Doneus & Briese 2007.) Airborne Laser Scanning (ALS), *the airborne variant of LiDAR,* has increased the research possibilities in forested areas in a spectacular way *(*Doneus & Briese 2011, Doneus et al. 2022). LiDAR, like RADAR, is an acronym and stands for light detection and ranging, which describes the method of determining three-dimensional data points by the application of a laser. It is an active remote sensing technique, using either ground-based (Terrestrial Laser Scanning (TLS) or airborne systems (Airborne Laser Scanning (ALS) (Pfeifer & Briese 2007).

Fernandez-Diaz et al. (2014) discuss each step of the workflow of the use of ALS from choices of the data acquisition till final archaeological interpretation. They argue rightfully that each decision with a step in the whole workflow has consequences for the final outcome. Therefore, it is of importance to know what you are doing to answer your research questions. Lozić & Štular (2021) also have a critical perspective on how ALS data is used for archaeological purposes and how the methodological steps are documented. They suggest a new workflow with appropriate terminology to make all steps in the research transparent and accountable. In addition, Štular et al. (2021) argue that instead of a DTM should be created for specific archaeological features a so-called Digital Feature Model DFM. A DFM makes use of ground points, buildings for contextual information and a morphological type of an archaeological feature. The best choices for each step in the workflow of the use of ALS are fundamental to optimize the DFM. Further a DFM confidence tool is presented for evaluating the quality of the DFM. As roads and paths are imbedded features, good quality DTM already offer good opportunities for road and path research. A 3-D model of the ground surface can be built from the returning pulses which are not blocked by the tree canopy. This explains why we can expect more returning pulses from the ground surface with deciduous trees in the wintertime. However, the surface cover, such as piles of leaves or brush, and snow height also affect the quality of the laser scanning. Although some issues, like filtering of undergrowth, still have to be resolved in a better way, the applicability of these advances in ALS is enormous. It has been used successfully in forested areas in different landscapes all over the World (Sittler 2004, Challis 2006, Lertlum & Shibayama, 2009, Hesse 2010, Fernandez-Diaz 2014, Chase & Chase 2020). Often it leads to an increase of known archaeological features. For example, in the Netherlands the number of known prehistoric field systems (so called “Celtic fields”) has increased dramatically through the use of ALS data (Kooistra & Maas 2008). Good results have also been obtained using ALS for the measurement of even subtle (linear) structures (Doneus & Briese 2007, Kooistra & Maas 2008). Moreover, linear features can be followed using large ALS datasets at a landscape scale (Doneus & Briese 2007). This is of great importance for the detection and extraction of regional road networks. Indeed, the visibility of features are crucial for detection and extraction. In the last decades several researchers have developed visualisation techniques to enhance the visibility and thus the possibility for extraction (Hesse 2010, Doneus 2013, Kokalj & Hesse2017).

Experience shows that an ALS dataset over a forested area usually contains a multitude of roads, paths, hollow ways and trackways. In order to accelerate the mapping of road and path networks from ALS data, the optimal way to (semi-) automatically extract these linear features from an ALS-derived digital terrain model (DTM) has been investigated (Sevara et al 2016, Kazimi et al 2018, Ni et al 2021). The specific use of ALS for road research has been published in several articles. The naval postgraduate school of Montery has carried out several researches. Espinoza et al (2007) investigated the usefulness of ALS in identifying roads and trails in four different forested areas. They found that trails and roads with a size of one meter could be identified based on small depressions in the DTM. If these depressions were missing, trails and roads could be missed. Karatolios& Krougios (2008) took the research further and investigated the usefulness of the Quick Terrain Modeller software. The latter is used by the same researchers to visualize the ALS data The intensity of ALS data, also investigated in this dissertation, is discussed to discriminate between roads and other objects. They found difficulties visualizing unpaved roads and paths. Another investigation by the same postgraduate school was done by Harmon III. He tested ENVI software, developed for multispectral and hyperspectral images for the automatic detection (visualisation) of roads and trails applying curvature, slope, hill shade and convexity, leading to a multilayer data set. Classification techniques were investigated and the maximum likelihood classifier resulted as best in characterizing unpaved and trail segments. A percentage of over 83% of true positives is given before image processing. However, the precision rate is only 43,6 %, which is visible in the corresponding image, in which a lot of noise is still visible. This makes the usefulness of this method for extraction questionable and the final presented thematic map also looks blurry.

Also the accuracy of ALS scans of a forest road was tested by comparing it with field research data by White et al (2010). The accuracy was 95 % of the digitized road lying within 1,5-meter distance of the centreline of the field data. The slope and road length were also calculated with high accuracy. In other words, ALS is suitable for measurements. Next, Sherba et al (2014) carried out a road extraction using an object-based approach combining slope and region growing to extract logging roads in California. A line-intercept field sample was used for classification and validation of the model. Although good results were obtained by the technique developed by these researchers, there was some misclassification of roads on ridge line and streams. More interesting is to know if this application will be feasible on small roads and paths with little slope difference,especially in areas where relief differences are low like in the Veluwe.

More specifically regarding extraction, based on a slope model, Rieger et al (1999) applied the break line concept to extract roads from ALS. The break line technique needs sharp breaks of the road sides in order to be discerned. Often break-line software delivers short edges; therefore, before extraction the DTM is pre-processed by the biased sigma filter which sharpens the edges and leads to enhancement of the edges. For extraction, the Förster operator is used. Finally, to connect broken and separated segment they use snakes, leading to longer segments. Comparison with geodata from field survey showed a displacement of 2 meter in y-direction and 1.2 direction. This displacement for broad roads to which they applied their research may be not significant. However, for smaller roads and paths, like in the Leitha Hills and Veluwe, the displacement could be significant. Moreover, the break lines takes both sides of the roads and other parallel lines (noise), as shown in their images. Often only one centreline is needed. In other words extra processing steps are needed, which could be complicated with several parallel lines and noise. Therefore a semi-automatic approach is suggested. The break line concept has also been tested in this dissertation.

David et al. (2009) apply instead another method to extract roads in forested areas. Indeed, based on the point cloud three images have been created: an nDSM, altimetric variance map and an intensity map. A statistical selection method based on parameters for all three images is used to detect seeds. Then a region growing algorithm has been applied to connect seeds and create longer road segments. A vectorization process has been carried out, with the creation of a centre-line being the last step. The authors doubt the usefulness of a nDSM for forested areas. One of their conclusions is that the data quality of their method is not sufficient yet to semi-automatically mapping of roads in forested areas. This line of investigation is not used in the dissertation.

Regarding the use of ALS for relative dating of roads and paths, several articles have been published and they all engage with the complexity of it (Hesse 2013, Mlekuž 2013, Nuninger et al. 2020). In this dissertation also a chronological model for historical roads and paths is presented.

Predictive modelling of lost roads and routes has been practised for decades in archaeology; in such modelling, slope was often the decisive factor (Herzog 2017). Nowadays also attempts are made to include social and cultural factors (van Lanen 2015, Herzog 2017, Parcero-Oubiña et al. 2019 Verhagen et al. 2019). The inclusion of cultural factors and physical factors other than slope are investigated in this dissertation.

The digital reconstruction of the landscape specific for historical road research is not or very little applied, especially in a gaming environment. Nevertheless, landscapes have been reconstructed for archaeological research purposes. (Ch’ng 2007, Chʼng and Gaffney 2013. Reinhard 2019). Due to the above mentioned the use of gaming software for historical road reconstruction dealt with in this dissertation is quite new.

The results of the above-mentioned investigations have determined the subsequent components of the planned dissertation. The methods have been tested, and the results of these tests establish the applicability of the methods in the research areas. Therefore, a step-by-step work plan has been set up. These steps will be described in more detail.

1.4 Methodological Topics

Based on the sub questions of this dissertation, the topics of the methodology are described below. In the corresponding chapters, these topics are worked out in more detail and are also reflected in the structure of the dissertation presented in paragraph 1.6.

1.4.1 Semi-automatic extraction

The automatic or semi-automatic extraction of roads and paths from ALS data is an important step. The main reason to carry out the extraction is the time gain that can be achieved. However, also the quality plays an important role, because too much ‘noise’, in other words unwanted features, will lead to extra elaboration. This can be even more laborious than manual mapping of features. In order to find a good method, different visualisation techniques of ALS data and extraction techniques will be tested. In practice, this means that different software packages will be investigated.

1.4.2 Time-depth of road and path systems (relative chronology)

Once the road and path networks in a study area have been detected, they will be augmented with other data sources. This is part of the interdisciplinary approach. However, it remains difficult to determine the age of the roads and paths. This is a problem which is not easy to solve, especially with regard to older roads and paths. Nevertheless, there is the possibility to determine the relative chronology by examining erosion, stratigraphic relations at intersections and geomorphology. Indeed, by using this information, a relative chronology within the path network can be established by means of existing software packages and old maps. The resulting relative chronology model can give significant insights into the development of road and path networks in the past. Therefore, it is worth investigating software packages for their capacity to determine the historic time depth paths and roads.

1.4.3 Predictive modelling of unknown networks

The detected road and path networks reflect only partly the whole range of road and path networks which once existed. Together with information of the (paleo-) environment, models can be developed in which the missing parts can be predicted. Together with the extracted roads and paths, a more complete picture of historic roads and paths can be created. For this reason, modelling is a necessary technique for discovery and analysis of prehistoric and historic road and path networks. It is also of interest to compare the outcome of the model with the extracted roads and paths, and other known historic networks. Indeed, it can shed a light on the validity of the model developed.

1.4.4 Visualised reconstruction

The geometry (shape), location and attributes (e.g. ownership) of roads and paths can change over time. The changes can be visualised in a GIS in static, kinematic (animation) and dynamic maps, which have several analytical possibilities. These kinds of maps have all proved to be very useful. However, they are often limited in their visual presentation. Game engines can create more realistic models (reconstructions) of landscapes. It would be worthwhile, if both strengths could be combined. In other words, uniting the analytical possibilities of a GIS and the visual presentation of a gaming engine. In this way, a gaming engine will be an important tool, which is not confined to the representation of the output but will be used as a tool for further interpretation of the road and path networks. Therefore, a gaming engine will be investigated for its possibilities for temporal visualisation of historical roads and a comparison will be made between the analytical results of a GIS and the gaming engine.

1.5 Selection and description of case studies

Selection of case studies

To operationalize the newly developed techniques and routines that are described above two interdisciplinary case studies were selected as test areas. These case studies are: (1) the Leithagebirge (Leitha hills) in Austria about 40 km Southeast from Vienna; and (2) The Veluwe area in the Central Netherlands.

The reason for this choice is that these areas have important characteristics in common:

- for both areas good ALS data availability (high resolution of DTM (0,5 m) and availability of raw data) are available;
- both areas are covered mainly by forested or vegetated areas;
- the settlement traces in these areas have sufficient time depth from at least Neolithic onwards;

- in both areas a (pre-)historic road and path networks exist;
- the PhD student has relatively easy access to conduct fieldwork in both areas.

Although both case-study areas have some characteristics in common, they are part of two completely different landscapes. The Leitha hills are formed by tectonic movement lifting old marine (calcareous) sediments upwards. The Veluwe area is formed by push moraines and covered with conifer trees and large stretches of heathland on sandy soils. The developed methodology of systematic application of ALS for the reconstruction of road and path networks will be tested and discussed in both settings.

For the Veluwe area, data have been provided by the Dutch National Board of Water management and for the Leitha hills by the Department for Prehistoric and Historical Archaeology of the University of Vienna (IUHA). Other data needed were provided by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro). Both case-studies have a large scale in both time and space.

Short description of case study area 1 – The Leitha Hills (Austria)

The Leitha Hills are a range of hills in South-eastern Austria. The name Leitha is derived from the river Leitha which runs parallel on the northwest side of the area. The hills are about 35 km long and 5 to 7 km wide (figure 8). The hills are considered to be middle mountains and connect the Alps with the Carpathians. The Sonnenberg, at 484 m above sea level, is the highest point. On the northwest side there is the Leitha river as part of the Wiener basin and on the southeast side the adjacent flat land runs into the marshes of the lake Neusiedlersee. The Leitha Hills are mainly forested with exception of a small heathland zone in the Northwest. Oak, hornbeam and birch are the predominating tree species (Krizsanits and Horvath 2012).

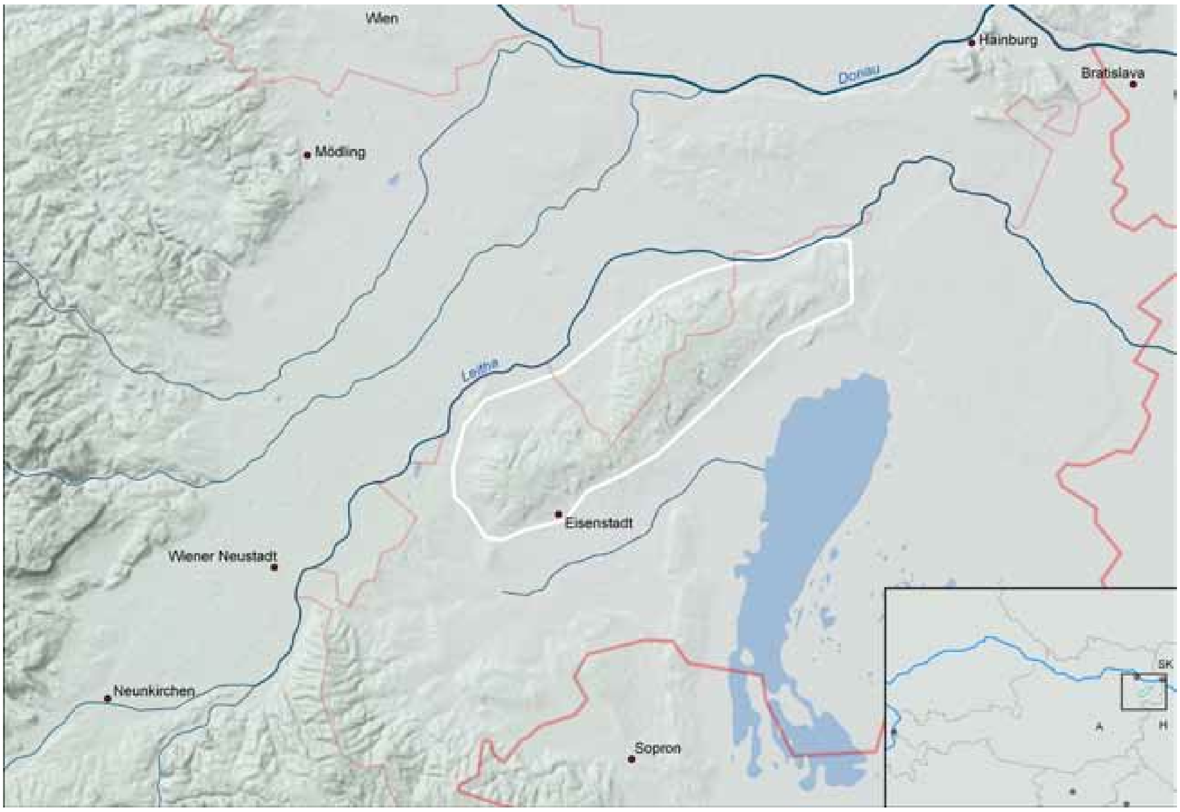


Fig. 9. The Leitha Hills outlined in white (Doneus and Briese, 2011)

Short description of case study area 2 - The Veluwe (The Netherlands)

The Veluwe area is a forest-rich ridge of sandy glacial moraine ridges (ca. 1100 km^2) located in the central part of the Netherlands (Figure 2). The region features many different landscapes including large sand drifts, woodlands and heaths. The most striking characteristic of the Veluwe is the presence of relatively high ice-pushed moraines formed during the Saalian glaciation (c. 240.000-130.000 years ago). Additionally, the Veluwe contains some very long cover-sand ridges and snowmelt water valleys. Relief in the region nowhere exceeds 110 meters (the highest point of the push moraines) and slopes are generally gradual.

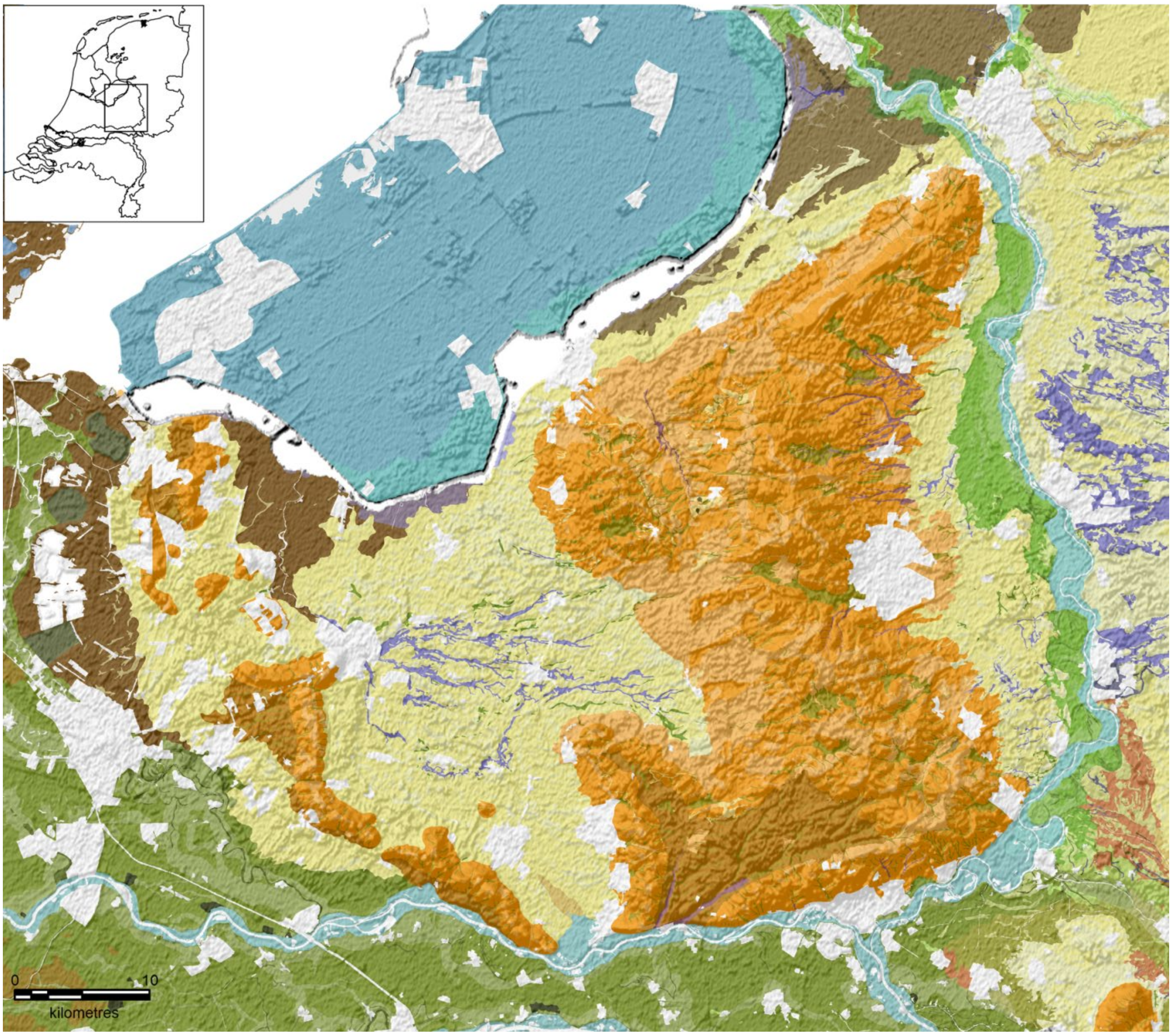


Fig. 9 The Veluwe is the large orange polygon on the right (Vletter & van Lanen, 2018).

1.6 Structure of the thesis

This PhD dissertation is paper-based, in other words it is built up out of articles that are peer reviewed. All the above-mentioned steps of the methodology form topics which contain published articles in (mostly peer reviewed) journals. Each article is a chapter in the dissertation and altogether, they constitute the main body of the dissertation. The articles will have at least a short introduction to provide information regarding the publication. Next to the main body of articles regarding the methodology applied to the case study areas, there is in the end a general discussion chapter about the applied methodology and research questions. The composition of the dissertation is described below.

Topic I – Extraction and Mapping of Roads

For this topic the following papers are presented as chapters:

“(Semi-) automatic extraction from Airborne Laser Scan (ALS) data of road & path in forested areas”. This paper deals with the extraction of roads and paths from ALS. Four extraction techniques are discussed and the best one considered is applied to both study areas. The results of the comparison of the extraction techniques and the outcome for the study areas are presented here. These outcomes give the base for further development of the methodology for the use of ALS for historical pahtways research.

“A workflow for (Semi)-automatic extraction of roads and paths in forested areas from Airborne Laser Scan data”. In this article, the workflow of extraction developed paper is presented and the importance of export knowledge is briefly discussed.

- “Extraction issues”. In this chapter the issues which came forward during the extraction are discussed and possible solutions have been tested. The results of these tests are shown.

Topic II – Chronological Models

For this topic the following papers are presented as chapters :

- “Creating a chronological model for historical roads and paths extracted from Airborne Laser Scanning data”. In this paper, relative and absolute dating techniques are discussed. Further a digital tool OCRE is presented to show how relative dating can be carried out. This forms a building stone for relative dating in the methodology.
- “The relative chronology of the road network in the Leitha Hills”. In this paper the relative dating for the case study area the Leitha Hills is carried out. It gives insight how historical sources and ALS data can support each other to create a relative model.
- “Archaeological features and absolute dating of historical road tracks in the North-western European Sand Belt.: An interdisciplinary case study of a late medieval and early modern trade route at the Hoge Veluwe National Park (Central Netherlands)”. This paper shows that the absolute dating technique Optimal Stimulated Luminescence (OSL) can be used to show the chronical development in an excavated cart track. It broadens the initial methodology with an absolute dating technique for sandy soils.

Topic III – Reconstruction of Roads

For this topic the following papers are presented as chapters:

- “Finding vanished roads. Applying a multi-modelling approach on lost route and path networks in the Veluwe region, the Netherlands.” In the article, two different predictive models have been applied and compared. Furthermore, they have been validated by historical maps from different periods. This article gives insight into the importance of cultural data for modelling and how the influence of factors in a model can variy. It contributes to the methodology as prediction is a crucial step for historical pathway research.

- “First steps for the use of a gaming engine for historical road and path research”. In this article a gaming engine is tested for modelling for historical route reconstruction and compared with the modelling in standard software. Further the (future) possibilities of gaming engines to enhance historical pathway research are discussed and, in this way, the reconstruction step of the methodology is amplified.

Chapter 10 General discussion

In this final chapter, the outcome of the dissertation and each of step of the methodology will be discussed. For this, the results, issues, related research, and future possibilities of each methodological step will be presented. Also for each step the success of answering the research questions and the contribution to the archaeological field will be discussed. The chapter ends with final remarks about the dissertation.

Appendixes.

In this part a summary of the research is given in English and in German for German-speaking scholars at the University of Vienna and beyond.

Literature

Argote-Espino, D., Chavez, R. (2005). Detection of Possible archaeological Pathways in Central Mexico through Digital Processing of Remote Sensing Images. *Archaeological Prospection,* 12, 105–114.

Aston, M. (1985). *Interpreting the landscape. Landscape Archaeology in local studies*. London: B T Batsford.

Bakker, J. A. (1976). On the possibility of reconstructing roads from the TRB period. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek Amersfoort*, *26*, 63-91.

Baumann, M. (1992). Flüsse als europäische Verkehrsadern. Eine Skizze am Beispiel des Hochrheins. – *In H. Berger, C Brunner and O. Sigg. Mundo multa miracula. Festschrift für Hans Conrad Peyer*. 82−96.

Bishop, M. C. (2014). *The Secret History of the Roman Roads of Britain: And their Impact on Military History*. Pen and Sword.

Brolsma, J.U. (2010). *Beknopte geschiedenis van binnenvaart en vaarwegen.* Delft: Ministerie verkeer en waterstaat.

Carballo, D. M., & Pluckhahn, T. (2007). Transportation corridors and political evolution in highland Mesoamerica: Settlement analyses incorporating GIS for northern Tlaxcala, Mexico. *Journal of Anthropological Archaeology*, *26*(4), 607-629.

Ch’ng, E. (2007)._Using Games Engines for Archaeological Visualisation: Recreating Lost Worlds. *Computer Games’07, The 11th International Conference on Computer Games: AI, Animation, Mobile, Educational & Serious Games,* La Rochelle, 21-23 November 2007, 26-30.

Ch′ng, E., Gaffney, V.L. (2013). Simulation and Visualisation of Agent Survival and Settlement Behaviours in the Hunter-Gatherer Colonisation of Mesolithic Landscapes. In: Ch'ng, E., Gaffney, V., Chapman, H. (eds) Visual Heritage in the Digital Age. Springer Series on Cultural ComputingSpringer, London. , 235-258 https://doi.org/10.1007/978-1-4471-5535-5_12

Chadwick, A. M. (2007). Trackways, hooves and memory days–human and animal memories and movements around Iron Age and Romano-British rural landscapes. In: V. Cummings, R. Johnston eds. *Prehistoric Journeys.* Oxford: Oxbow. 131–152.

Challis, K. (2004, January). Airborne Lidar: A Tool for Geoarcheological Prospection in Riverine Landscapes. In *European Association of Archaeologist, Annual Conference, Lyon, France*.

Challis, K. (2005). Airborne LIDAR: A Tool for Geoarchaeological Prospection in Riverine Landscapes. *In:* H. Stoepker, ed. Archaeological Heritage Management in Riverine Landscapes. *Rapporten Archeologische Monumentenzorg*, 126, 11-24.

Chase, A. F., & Chase, D. Z. (2001). Ancient Maya causeways and site organization at Caracol, Belize. *Ancient Mesoamerica*, *12*(2), 273-281. https://doi.org/10.1017/S0956536101121097

Chase, A.S.Z., Chase, D. and Chase, A., 2020. Ethics, New Colonialism, and Lidar Data: A Decade of Lidar in Maya Archaeology. *Journal of Computer Applications in Archaeology*, 3(1), 51–62. DOI: http://doi.org/10.5334/jcaa.43

Darling, J. A. (2009). O'odham Trails and the Archaeology of Space. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*.University of Pennsylvania Press. 61-83. http://www.jstor.org/stable/j.ctt3fhjb3.10

David, N., Mallet, C., Pons, T., Chauve, A., Bretar, F. (2009). Pathway detection and geometrical description from ALS data in forested mountaneous area. *In:* F. Bretar, M. Pierrot-Deseilligny and G. Vosselman, eds. *Laser scanning 2009*, ISPRS, 38 (3/W8), 242-247.

De Laet, V., Paulissen, E., & Waelkens, M. (2007). Methods for the extraction of archaeological features from very high-resolution Ikonos-2 remote sensing imagery, Hisar (southwest Turkey). *Journal of Archaeological Science*, *34*(5), 830-841.

Denecke, D. (2007a), Wege und Wegenetz. In: Reallexikon der Germanischen Altertumskunde 35. Berlin, New York: de Gruyter, pp. 626–648.

Denecke, D. (2007b). Linienführung und Netzgestalt mittelalterlicher Verkehrswege – eine raumstrukturelle Perspektive. In: R.C.Schwinges, ed. *Strassen- und Verkehrswesen im hohen und späten Mittelalter*. Ostfildern: Jan Thorbecke, 49-70.

Doneus M., Banaszek Ł., Verhoeven G.J. (2022). The Impact of Vegetation on the Visibility of Archaeological Features in Airborne Laser Scanning Datasets from Different Acquisition Dates. *Remote Sensing*. 2022; 14(4):858. https://doi.org/10.3390/rs14040858

Doneus, M. (2013). Openness as visualization technique for interpretative mapping of airborne lidar derived digital terrain models. *Remote sensing*, *5*(12), 6427-6442. 10.3390/rs5126427.

Doneus, M., Briese, C. (2011). Airborne Laser Scanning in Forested Areas - Potential and Limitations of and Archaeological Prospection Technique. *In:* D. Cowley, ed. *Remote Sensing for Archaeological Heritage Management*. Budapest: Archaeolingua, 53 - 76.

Doneus, M., Briese. C. (2007). Full-waveform airborne laser scanning as a tool for archaeological Reconnaissance In: S. Campana and M. Forte, eds. *From Space to Place. BAR International Series 1568* Oxford: Archeopress, 99-105.

Doneus, M., Wieser, M., Verhoeven, G., Karel, W., Fera, M., & Pfeifer, N. (2016). Automated archiving of archaeological aerial images. *Remote Sensing*, *8*(3), 209. https://doi.org/10.3390/RS8030209

Doswald, C. (2014). Die alte Schollbergstrasse. vom archäologischen Befund zum regionalen Wanderweg. In: *Wege und Geschichte.* Zürich: Chronos Verlag, 32-38.

Elerie, J. N. H., & Spek, T. (2010). The cultural biography of landscape as a tool for action research in the Drentsche Aa National Landscape (Northern Netherlands). In J. H. F. Bloemers, H. Kars, A. van der Valk, & M. Wijnen (Eds.), *The Cultural Landscape & Heritage Paradox. Protection and development of the Dutch archaeological-historical landscape and its European dimension* Amsterdam: Amsterdam University Press, 83 - 113.

Erickson, C. L. (2009). Agency, Causeways, Canals, and the Landscapes of Everyday Life in the Bolivian Amazon. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective* University of Pennsylvania Press, 204-231http://www.jstor.org/stable/j.ctt3fhjb3.16.

Erickson, C. L., & Walker, J. H. (2009). Pre-Columbian Causeways and Canals as Landesque Capital. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective* University of Pennsylvania Press,232-252http://www.jstor.org/stable/j.ctt3fhjb3.17

Erickson, Clark L.; Snead, James Elliott; Darling, J. Andrew (Hg.) (2009): Landscapes of movement. Trails, paths, and roads in anthropological perspective. Philadelphia: University of Pennsylvania Press. Online verfügbar unter http://www.jstor.org/stable/10.2307/j.ctt3fhjb3.

Espinoza, F., Owens, R. E., & Abrams, M. C. (2007). *Identifying roads and trails hidden under canopy using LIDAR* (Doctoral dissertation, Naval Postgraduate School).

Fernandez-Diaz, J. C., Carter, W. E., Shrestha, R. L., & Glennie, C. L. (2014). Now you see it… now you don't: Understanding airborne mapping LiDAR collection and data product generation for archaeological research in Mesoamerica. *Remote Sensing*, *6*(10), 9951-10001.

Geiss, P. G. (2021). Central Asia and the Silk Road: economic rise and decline over several millennia. Cham, Springer,

Gerking, W. (2013). *Alte Wege und neue Straßen in Ostlippe: eine geographisch-archäologische und historische Studie zur Erforschung alter Wege und zur Entwicklung des Verkehrsnetzes im 19. Jahrhundert*. Münster: Aschendorff.

Gibson, E. (2007). The Archaeology of Movement in a Mediterranean Landscape. *Journal of Mediterranean Archaeology*, 20(1), 61–87. DOI: https://doi.org/10.1558/jmea.v20i1.61

Guttormsen, T. (2007). Transregional Historical Roads in Local Landscapes: Via Egnatia in Macedonian Greece. *Die Erde,* 138 (1), Special Issue: Mediterreanan Landscapes, 97-116.

Harmon III, C. F. (2011). *Automating identification of roads and trails under canopy using LIDAR*. Naval postgraduate school Monterey CA.

Herzog, I. (2017). Reconstructing Pre-Industrial Long-Distance Roads in a Hilly Region in Germany, Based on Historical and Archaeological Data. *Studies in Digital Heritage*, 1 (2), 642-660. DOI: 10.14434/sdh.v1i2.23283

Hesse, R. (2010). LiDAR-derived Local Relief Models. A new tool for archaeological prospection. *Archaeological Prospection* 17(2), 67–72.

Hesse, R. (2013). The changing picture of archaeological landscapes: lidar prospection over very large areas as part of a cultural heritage strategy. In Opitz, R and Cowley, D (Eds.), *Interpreting archaeological topography: lasers, 3D data, observation, visualisation and applications*, Oxbow Books, 171–183.

Horsten, F. H. (2005). *Doorgaande wegen in Nederland, 16e tot 19e eeuw: Een historische wegenatlas*, Amsterdam: Aksant.

Karatolios, A., & Krougios, P. (2008). *Extracting hidden trails and roads under canopy using LIDAR*. Naval postgraduate school Monterey CA..

Kazimi, B., Thiemann, F., Malek, K., Sester, M., Khoshelham, K. (2018). Deep Learning for Archaeological Object Detection in Airborne Laser Scanning Data. In: A Belussi, R. Billen, P. Hallot, S. Migliorini. (Eds). *Proceedings of the 2nd Workshop on Computing Techniques for Spatio-Temporal Data in Archaeology and Cultural Heritage*, Melbourne, Australia, 25–28 August 2018,. 21–35.

Keller, A. H. (2009). A Road by Any Other Name: Trails, Paths, and Roads in Maya Language and Thought. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*,. University of Pennsylvania Pres, 133-157. http://www.jstor.org/stable/j.ctt3fhjb3.13

Köhler, M. (2015)*. Frühe Wege in den Landschaften zwischen Werra und Weisser* Elster. Jena: Jenzig-Verlag.

Kokalj, Ž., & Hesse, R. (2017). *Airborne laser scanning raster data visualization: a guide to good practice* (Vol. 14). Založba ZRC

Kolen, J., Renes, H., (2015). *Landscape Biographies. Key Issues. Geographical, Historical and Archaeological perspectives on the production and transmission of landscapes*. Amsterdam: Amsterdam University Press.

Konold, W. (2015). Die Prägung die Mitteleuropäischer Kulturlandschaften durch Jagdliche Nutzung. *In*: H. T. Porada, M. Heinze and H. Schenk, eds. *Jagdlandschaften in Mitteleuropa, SAGG, 32.* Bonn: ARKUM, 39-96

Kooistra, M.J., Maas, G.J. (2008). The widespread occurrence of Celtic field systems in the central part of the Netherlands. *Journal of Archaeological Science*, 35 (8), 2318-2328.

Krizsanits, B., Horvath, M. (2012). Das Leithagebirge. Grenze und Verbindung. Weitra: Bibliothek der Provinz.

Lertlum, S., & Shibayama, M. (2009). Application of Geo-informatics to the Study of the Royal Road from Angkor to Phimai. *Japanese Journal of Southeast Asian Studies*, *46*(4), 547-563.

Li, N., Kähler, O., & Pfeifer, N. (2021). A comparison of deep learning methods for airborne lidar point clouds classification. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *14*, 6467-6486

Liessmann, W. (2010). *Historischer Bergbau im Harz: Kurzführer*. Berlin, Heidelberg: Springer ,

Lozić, E., & Štular, B. (2021). Documentation of archaeology-specific workflow for airborne LiDAR data processing. *Geosciences*, *11*(1), 26.

Mlekuž, D. (2013). Messy landscapes: lidar and the practices of landscaping. In: Opitz, R.S. and Cowley, D.C. (Eds.), *Interpreting archaeological topography. 3D data, visualisation and observation. AARG Occasional Paper*. Oxford: Oxbow Books, 88-99. DOI: https://doi.org/10.2307/j.ctvh1dqdz.12

Murietta-Flores, P. (2010). Traveling in a Prehistoric Landscape: Exploring the Influences that Shaped Human Movement. *In:* B. Frischer, J. Webb Crawford and D. Koller, (Eds.). *Making History Interactive Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference (Williamsburg, Virginia, United States of America 2009). British Archaeological Reports, International Series* Oxford: Archaeopress, 249-267.

Nuninger, L., Opitz, R., Verhagen, P., Libourel, T., Laplaige, C. Leturcq, S., Le Voguer, N., Fruchart, C. Kokalj, Ž. and Rodier, X. (2020). Developing FAIR Ontological Pathways: Linking Evidence of Movement in Lidar to Models of Human Behaviour. *Journal of Computer Applications in Archaeology*, 3(1), 63–75. https://doi.org/10.5334/jcaa.46

Parcero-Oubiña, C., Güimil-Fariña, A., Fonte, J. & Costa-García, J.M. (2019). Footprints and Cartwheels on a Pixel Road: On the Applicability of GIS for the Modelling of Ancient (Roman) Routes. In: P. Verhagen, J. Joyce, M.R. Groenhuijzen (Eds.) *Finding the Limits of the Limes*, Computational Social Sciences. Cham: Spinger, 291-311. https://doi.org/10.1007/978-3-030-04576-0_14 .

Pfeifer, N., & Briese, C. (2007). Geometrical aspects of airborne laser scanning and terrestrial laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *36*(3/W52), 311-319.

Pijnacker, Cornelis, 1634. Kaart van Drenthe.

Reh, W., C. Steenbergen & Aten. D. (2007). *Sea of Land. The polder as an experimental atlas of Dutch landscape architecture*. Wormer; Amsterdam: Stichting Uitgeverij Noord Holland, Architectura & Natura Publishers.

Reinhard, A. D. (2019). *Archaeology of Digital Environments: Tools, Methods, and Approaches.* PhD thesis, University of York

Rieger, W., Kerschner, M., Reiter, T., & Rottensteiner, F. (1999). Roads and buildings from laser scanner data within a forest enterprise. *International Archives of Photogrammetry and Remote Sensing*, *32*(Part 3), W14.

Rodat, C. (2019). Altstraßenforschung als Archäoprognose - Methodische Überlegungen zu (prä-)historischen Wegen am Beispiel Westlicher Bodensee.

Sevara, C., Pregesbauer, M., Doneus, M., Verhoeven, G., & Trinks, I. (2016). Pixel versus object—A comparison of strategies for the semi-automated mapping of archaeological features using airborne laser scanning data. *Journal of Archaeological*

Science: Reports, *5*, 485-498.

Sherba, J.; Blesius, L.; Davis, J. Object-Based Classification of Abandoned Logging Roads under Heavy Canopy Using LiDAR. Remote Sens. 2014, 6, 4043–4060

Sittler, B. (2004). Revealing historical landscapes by using airborne laser scanning. A 3-D model of ridge and furrow in forests near Rastatt (Germany). *Proceedings of the ISPRS Working Group 8/2, Freiburg, Germany, 3-6 October 2004*, 258–261.

Snead, J. E. (2009). Trails of Tradition: Movement, Meaning, and Place. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.) *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*. University of Pennsylvania Press, 42–60. http://www.jstor.org/stable/j.ctt3fhjb3.9

Štular, B. (2011). Path networks.In: J. *Horvat, A. Pleterski, A. Velušček (eds.)* Opera in Instituti Archaeologici Sloveniae 23, Late antique fortified settlement Tonocov grad near KorbaridLjubljana: Collegium Graphicum, *, 53-64*

Štular, B., Lozić, E., & Eichert, S. (2021). Airborne LiDAR-derived digital elevation model for archaeology. *Remote Sensing*, *13*(9), 1855.

Szilagyi, M. (2014). *On the Road: The History and Archaeology of Medieval Communication Networks in East-Central Europe*. Budapest: Archaeolingua.

Ur, J. (2009). Emergent Landscapes of Movement in Early Bronze Age Northern Mesopotamia. In J. E. Snead, C. L. Erickson, & J. A. Darling (Eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective* University of Pennsylvania Press., 180-203.http://www.jstor.org/stable/j.ctt3fhjb3.15

van Lanen, R. J., Kosian, M. C., Groenewoudt, B. J., Spek, T., & Jansma, E. (2015). Best travel options: modelling Roman and early-medieval routes in the Netherlands using a multi-proxy approach. *Journal of Archaeological Science: Reports*, *3*, 144-159.

Verhagen, P., Nuninger, L. & Groenhuijzen, M. R. (2019). Modelling of pathways and movement networks in archaeology: an overview of current approaches. In: P. Verhagen, JJoyce &MR. Groenhuijzen (eds.), *Finding the Limits of the Limes: Modelling Demography, Economy and Transport on the Edge of the Roman Empire*. Cham: Springer, 217–249. DOI: https://doi.org/10.1007/978-3-030-04576 -0_11

Verhoeven, G. (2009). Beyond Conventional Boundaries. New Technologies, Methodologies, and Procedures for the Benefit of Aerial Archaeological Data Acquisition and Analysis. PhD Thesis. University of Ghent.

Vletter, W. F., van Lanen, R. J. (2018). Finding Vanished Routes: Applying a Multi-modelling Approach on Lost Route and Path Networks in the Veluwe Region, the Netherlands. *Rural Landscapes: Society, Environment, History*,. 1 – 19.

White, R. A., Dietterick, B. C., Mastin, T., & Strohman, R. (2010). Forest roads mapped using LiDAR in steep forested terrain. *Remote sensing*, *2*(4), 1120-1141.

Topic I – Extraction and Mapping of Roads

Chapter 2 (Semi-) Automated extraction from airborne laser scan data of road & path in forested areas.

This article has been published in *Proc. SPIE*. 9229, Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014), 92291D on 12 August 2014. The PhD student is the only author and thus the whole text is written by him. The article is peer reviewed and has been written after a presentation at the above mentioned conference. The content represents the first step of the methodology developed.

(Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas

Willem. F. Vletter*[a],
[a]Vienna Institute of Archaeological Science, Univ. of Vienna, A-1190 Vienna, Franz-Klein Gasse 1,
Austria +43-1-4277-404 75.

ABSTRACT

The possibilities of airborne laser scanning as a tool for visualisation and reconstruction of micro topography have been known for some decades. Indeed, in the archaeological field a lot of new features have been detected or reconfirmed. However, the task to map manually the enormous amount of features is time consuming and costly. Therefore, there is a need for automation. In this paper four workflows of visualisation and (semi) automatic extraction of (historical) roads and paths are compared. It proved that the concept of openness is preferred over the break line concept for visualisation. Regarding the extraction the software plug in Feature Analyst showed the best results. Openness and Feature Analyst stand also out when costs and processing time were considered. Therefore, we suggest the workflow which combines openness, for visualisation, and Feature Analyst for extraction. The results of this study contribute to the development of automatic extraction techniques in general. In this regard software packages like eCognition look promising to improve extraction methods.

Keywords: Archaeology, ALS, roads, forest, extraction, break lines, openness, intensity.

1. INTRODUCTION

Until recently, the application of prospection techniques in heavily vegetated or forested areas has been very problematic. This has had a negative impact on research of historical roads and paths, especially as they tend to be better preserved in this kind of areas. Over the last decade, Airborne Laser Scanning (ALS) has changed the situation. With this remote sensing technique it is possible to visualise on a large scale the micro topography of landscapes. Moreover, it can also be applied in heavily vegetated or forested areas. Therefore, it is now possible to conduct research on road networks on a large scale in these areas. This is exactly the case in the case study area of the Leitha Hills in Austria, because next to the great amount of archaeological features, there is also a huge quantity of linear features like road, paths and creeks. For the sake of time and money saving, (semi)- automatic extraction of these linear features would be fruitful. On ALS data roads and paths appear as longitudinal components and it is a challenge to separate that kind of components from others components that are detected. Already interesting research to the possibility of extraction of road features has been carried out. Nevertheless, the extraction of road information from LiDAR data on a broad scale is still in its infancy.[7] As a result, work still has to be done for automatic extraction of linear features. [1][2]

In this paper an attempt is made to develop a workflow for the extraction of roads and paths in forested areas. Four workflows are tested (see table 1). Each workflow exists out of visualization step and an extraction step. Regarding the visualization we wanted to apply a concept that was able to detect even the subtlest paths. The reason for this is that we are most interested in historical roads and paths. A lot of them are no longer in use. Consequently, over time erosion or human interference could have weakened their outline or even completely faded them away. Therefore, we opted for available visualization techniques which are able to show even subtle changes in micro topology. In the end both the break line and openness concept were selected. Both break lines and openness have been proved to be a good visualization technique [4][12], but none of them have been utilized specific for road extraction in forested areas. Another visualization technique, Local Relief Model developed by Ralf Hesse, was considered. However, a recent study proved it less suitable for the study area and therefore it is not taken into account.[12]

*willem.vletter@univie.ac.at; phone +43-1-4277-404 75; fax +43-1-422-9-404; http://ic-archpro.univie.ac.at/

Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014),
edited by Diofantos G. Hadjimitsis, Kyriacos Themistocleous, Silas Michaelides, Giorgos Papadavid,
Proc. of SPIE Vol. 9229, 92291D · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2069709

Further, the intensity characteristic of the LiDAR data was investigated at its usability for visualization, as full waveform data was provided by Technical University of Vienna. Intensity is considered one of the most interesting features of ALS. However because of its complexity, it has been little used. Nevertheless, in this paper it has been tested.

Regarding the extraction, we applied the following software packages; STREX, Feature Analyst and eCognition. STREX is built for the break line concept and the only software known for this concept. eCognition has a proven applicability for archaeological features visualized with ALS data.[16] Based on the information provided, Feature Analyst looked promising for feature extraction.

The paper has the following outline. First, in chapter two the data used for this paper are dealt with. Then, in chapter three and four, the mentioned visualization concept and extraction software are explained in more detail. In chapter five the results of the four work flows will presented and discussed. Finally, the paper will finish with a conclusion.

Table 1. The four workflows tested in this paper. For each workflow the data format, the (possible) pre-processing step, the used visualisation technique and extraction software are listed.

	1.	*2.*	*3.*	*4.*
Data format	*LAS*	*LAS*	*LAS*	*Full waveform*
Preprocessing	-	*DTM (SCOP++)*	*DTM (SCOP++)*	*OPALS*
Visualization technique	*Break Lines (STREX)*	*Openness (OPALS)*	*Openness (OPALS)*	*Intensity (OPALS)*
Extraction software	*STREX/ (SCOP++)*	*Feature Analyst*	*eCognition*	*Feature Analyst / eCognition*

2. DATA

Before working with ALS data, or any kind of remote sensing data, it is heavily recommended that one should get knowledge of the conditions, the technique and of the device used. Doneus and Briese already stressed extensively the importance of obtaining the meta-information.[5] They argue that meta-information constitutes an important aid to understand the archaeological potential and limitations of the DTM. An aspect that is often neglected or underestimated. Further, knowledge about the technology, metadata and algorithms is needed to carry out source criticism.[5] For the reason of the arguments above, the most important parameters of the ALS data are stated in table 2.

As can be seen in the table the ALS data are obtained during the project “LiDAR Supported Archaeological Prospection in Woodland” in the Leitha Hills. This is a forested area of approximately 190 square km, 40 km south of Vienna, which rises some 200m to 300m above the valley of the river Leitha. It is covered by a forest of mixed deciduous trees, mainly oak and beech with varying degrees of understory. [5]

The archaeological sites that have been detected, based on the created DTM are mostly medieval or post medieval. Summed up four late Neo Lithic hillforts, several Iron Age hillforts, round barrows, building structures stone quarries, hollow ways, medieval field systems, medieval border-markers (so called ‘Hotter’), hundreds of lime-kilns, military trenches from the post-medieval period to World War II and a large number of bomb craters from World War II have been interpreted. [1]

Table 2. The meta-information of the ALS data used in this paper. [5]

ALS-Project	Leitha Mountains
Purpose of Scan	Archaeology
Time of Data Acquisition	March – 12th of April 2007
Point-Density (pt. per sq. m)	7
Scanner Type	Riegl LMS-Q680i Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	36 m/s
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Robust interpolation (SCOP++)
DTM-Resolution	0.5 m

3. METHODS USED FOR VISUALISATION

3.1 Break lines

For the representation of the models computed on the basis of the acquired irregular distributed point cloud (ALS data) mostly raster resp. grid models or triangulated irregular networks (TINs) are in use, which only implicitly store break line information. However, for a high quality surface description the explicit storage of break lines within the data structure of these models is necessary. [4]

The advantage of the TIN, grid and raster approaches is that they work quite fast. However, a disadvantage is a loss of precision. This is a significant issue. In our research to historic roads and paths we deal with subtle changes of the surface. Therefore the ′quadric′ approach, as described by C. Briese et al, is more suited as the loss of precision is less. In this approach the detection of potential local break line segments is performed by the analysis of a locally determined 2.5D second order surface (quadric) q [6]:

$$q = f(x, y) = \sum_{i+j \leq 2} a_{ij} x^i y^j$$

In this approach a grouping of the point cloud into two groups takes place. Each group includes the points on either side of the break line, and subsequently reconstructs the surface on each side independently. This leads to two surface descriptions, which are valid for one side only. So, in a more technical sense, the definition of break line is: the intersection of two smooth surfaces, each surface interpolating the points on either side.[4] It is not the goal of this paper to discuss in detail the technical aspects. For the scope of the research it is sufficient to mention the main advantages of this approach; the high degree of accuracy and completeness. These advantages make this approach to be preferred over the raster, grid and tin based approaches.

It is important to remember that the concept of break lines was developed to extract structure lines to generate very accurate Digital Terrain Models. Nevertheless, this technique can also be applied for other purposes. In this case it will be used for the extraction of road and path networks.

3.2 Openness

The concept openness was first introduced by Ryuzo Yokoyama, Mlchlo Shlrasawa, and Richard Pike in 2002 and they defined openness as follows: a parameter expressing the degree of dominance or enclosure of a location on an irregular surface is developed to visualize topographic character.

Openness is an angular measure of the relation between surface relief and horizontal distance. For angles less than 90 degrees, it is equivalent to the internal angle of a cone, its apex at a DEM location, constrained by neighbouring elevations within a specified radial distance. Openness incorporates the terrain line-of-sight, or view shed, concept and is calculated from multiple zenith and nadir angles. Openness has two viewer perspectives. Positive values, expressing openness above the surface, are high for convex forms, whereas negative values describe this attribute below the surface and are high for concave forms. Openness values are mapped by grey-scale tones.[11]

As opposed to various shading techniques, openness is not subject to directional bias and relief features highlighted by openness do not contain any horizontal displacement, which is imperative for accurate interpretative mapping. Additionally, it offers a clear distinction between relief features and the surrounding topography, while it highlights both the highest and lowest parts of features. This makes openness an ideal tool for mapping and outlining of archaeological features. Furthermore, as openness can outline features, it has the potential to function as a basis for (semi-)automatic classification based on pattern recognition and image classification algorithms.[11] This makes openness very interesting as most of the visualization techniques help the user to perceive archaeological and palaeoenvironmental features, but not all of them are helpful when trying to delineate individual structures during interpretative mapping.[12]

3.3 Intensity

Another possible technique for the visualisation of road and paths is intensity. It is defined as the characterisation of the backscattered signal strength of an echo. However, often this specification is not accurately defined. In that the term intensity can for example express the maximum as well as the total energy of one echo.[13] In our case we will estimate the signal intensity as the product of the full waveform attributes amplitude and echo width.[14] This means that for calculation of the intensity we need the full wave recording. The main value of using a full-waveform recording scanner is the availability of additional physical observations of the reflecting surface elements, which can be useful for object classification.[2] In the full waveform format these additional physical observation are stored. As mentioned above for our purposes, we need for the calculation of the intensity the echo width and the amplitude. The echo width provides us information on the range distribution of all the small individual scatters contributing to one echo. The amplitude gives information about the radiometric scattering properties of the illuminated targets that contribute to one echo. For example if the echo width is small, a rather flat surface element was illuminated. However, when it is large, scatters at different ranges contribute to the one determined echo.[6] In addition, the amplitude can give us extra information on the quality of the reflection. Nevertheless, the difficulty is to use the amplitude for classification purposes. The reason for this is that different effects like footprint area, the scattering directionality, size, topography, vertical distribution, and reflectivity of the target contribute to single amplitude. The recorded intensity values are very noisy and additionally, a lot of systematic effects can be recognised due to the fact that these intensities are not calibrated.[4] This makes it rather complicated to use intensity for classification purposes and explains why the intensity of the received echo is very rarely used. Nevertheless, through using amplitude and echo width to calculate intensity, it is possible to investigate the return signal and extract additional ground characteristics, as was shown in earlier tests in the research area.[6]

4. SOFTWARE APPLICATIONS FOR EXTRACTION

4.1 STREX

In order to extract break lines from ALS data the software package STREX was used. STREX stands for structure line extraction. This package has been developed by the Technical University of Vienna. Applying this package is not only useful for the goal of this research, but also contributes to general investigation of the local adoption of processing parameters.[4] It makes use of an algorithm that for each point in the point cloud calculates the curvature within a certain number of surrounding points.

STREX software runs in a DOS environment. It has three processing steps (command lines); detection of structure line (strex.exe), the break line finder (breaklf.exe) and post processing structure line data (strexp.exe). They run in the mentioned order. However, it possible to run all the processing steps separately in the DOS shell. Strex.exe allows the extraction of structure line segments (initial start segments) based on point cloud data. Breaklf.exe models structure lines based on surrounding point cloud data and given 2D start-segments (result of STREX or manual input). Strexp.exe allows the refinement of the automatically generated lines. Each processing step consists out of a set of arguments (parameters), which can be changed. According to changed settings different output will be generated.

4.2 Feature Analyst

Feature Analyst is software plug-in tool from GeoEye and is compatible with ArcGIS and Erdas Imagine. As accounts for STREX also Feature Analyst has parameters, which should be optimised to get the best results. The first step is digitising a training set and the software is run. It can be followed up by different steps which eventually lead to a model that can be used for batch processing. It is a quite easy and straightforward software package.

4.3 eCognition

A last software package that is tested is eCognition. This package has a lot of possibilities and it goes beyond the scope of this paper to explain it in detail. The most important notion to make is that it can work both with radiometric and geometric characteristics, also in combination. Like in Feature Analyst a model must be built, which can be used for batch processing. It has already proved to deliver excellent results for extracting archaeological features in a short time, less than a day.[16] However, before eCognition can be fully exploited the program has to be learned and this takes some time.

5. RESULTS AND DISCUSSION

.

Some aspects of the break line approach in STREX of workflow 1 are worthwhile to take a closer look at. For example the delineation of the whole line is not performed by the connection of neighboured and similar oriented break line segments. Instead of this procedure the concept of break line growing was utilised. Immediately the question rises which concept is more adapted for connecting break line segments (part of roads) to create a network. Therefore further research for the determination of a reliable break line network is needed. Regarding the break line growing procedure, it needs improvement in areas of strongly curved lines.[5]

The refinement (strexp.exe) step is also intriguing. On the one hand it removes short gaps, which seems positive, for creating a network. However, on the other hand in this step also short line elements are removed. However, these short line elements could be remains of historic (not vanished) roads and paths, and therefore of interest. For this reason this step was left out.

The results of STREX can be seen in figure 4. A disadvantage of the technique is that two or more lines can be depicted for roads and paths, especially the ones which have strong edges (“breaks”) on either side. This happens mainly with the broader (modern) roads. As the research is more focused on subtle roads, the problem of plural linear features for one road is an issue of minor importance. In trying to optimize the final results a trade-off must be made between the quantity and quality. In other words, changing the parameters of the different steps to increase the number of extracted linear features leads not only to a higher number of roads or paths but also to higher number of noise features.

This kind of trade-offs accounts for all three methods applied in this article. Both researchers tried separately the STREX software and came more or less to the same parameters settings. Another disadvantage is that before the results of the post processing (refinement) can visualised in ArcGIS a conversion has to be carried out in another software of the TU, SCOP ++. A solution for combining different kind of roads (based on different parameter settings) would be using the Merge application in ArcGIS. This works fine, but constitutes an extra elaboration step and thus time. It necessary to mention that in work flow 1 the visualisation and extraction are both carried out in STREX.

Before discussing openness, used in both workflow 3 and 4, it is interesting to take a look at the input DTM. The provided DTM was created by using robust interpolation (RI) in SCOP++. This interpolation flattens to a certain degree micro topographic features.[1] Immediately the question arises how this influences the visibility of subtle road and path features on the DTM. Therefore, when the results of the extraction techniques are confronted with the DTM, one should be aware that some of the subtle path and tracked features have been flattened out. One should also remind that RI filtering results in a DTM, which is one of the possible representations of the relief.

We applied the concept of openness within in the software package OPALS of the Technical University of Vienna (TU). Is an acronym of Orientation and Processing of Airborne Laser Scanning data.This software package has a module called openness. The module is run in a DOS environment. After several test runs it was concluded that openness with a kernel size of 5 led to the best results, as with this setting also subtle linear features were detected.

A possible following up step is the elaboration in Photo Shop, where in the High Dynamic Range (HDR) the visualisation can be improved. However, a significant disadvantage is that changed images in Photoshop lose their geographical information. This is an issue can be resolved but a plug-in for Photo Shop is needed. Even though batch processing is probable, it will lead to an extra elaboration step and therefore time consuming. Moreover, the results between HDR elaborated images and the ones with no HDR elaboration didn´t show significant differences. For this reason it was decided to surpass this extra step.

Another complication emerged during elaborating the openness images in Photoshop. It resulted that tiles without a complete coverage (areas without ALS data) didn´t deliver good results in OPALS. This was even the case when a small part lacked. Therefore for these images the optimisation in Photo Shop wasn´t possible, which means that roads and paths would have to be drawn completely manually.

The TUV provided a tile of the laser scan of the Leitha Hills area in the needed full waveform (fwf) format which was imported in the OPALS software and used in workflow 4. In this software the last echoes were selected, the intensity was added (echo width multiplied by amplitude), and the intensity values were exported in a gridded TIF file.

In the figure 1 the outcome of the intensity visualization is compared with openness. An advantage of this technique is that scarcely any water flow is detected and only roads are visible. This is not the case with the techniques of openness and break lines, where it is sometimes hard to discern a creek from a path. However, there is also a disadvantage of intensity regarding openness and break lines. Intensity is (yet) not able to discern small paths. This is probably caused by the fact the data comes from a forested area and therefore there is a lot of noise which decreases the backscattering. Another possible reason may be that paths, especially small ones, differ very little in backscattering values from their surroundings. Nevertheless, the quality of the intensity can be improved by calibration. In OPALS there is a module made for this objective. However, to run this absolute calibration task in situ reflectance measurements of reference surfaces within the project area are required.[15] Also calibration can be based on homogeneous plain. The in situ reflectance data were not available. Moreover, it was not expected that calibration in this stage would lead to such an improvement, that it would be comparable with the visualization of the small linear features of break lines and openness. As the quality differed so much with those two concepts, as can see in figure 1, no extraction was carried out for work flow 4. Also other packages like LP360 and Fusion were also considered and even tested, but they didn’t prove suitable or there were some not resolved processing issues.

Figure 1. On the left an openness image of 1 square km of the research area is shown and on the right intensity image of the same area. It is clear that openness has visualized a lot more linear features than intensity.

In the extraction step of the workflow 2 the openness images were imported in ArcGIS, where the Feature Analyst plug-in tool from GeoEye is used. As has been mentioned before, in this software package a model should be built. As

accounts for the others software applications in this study also Feature Analyst has parameters, which should be optimised to get the best results. The first step, maybe the most important one, is digitising a training set and run the software. It can be followed up by different steps which eventually lead to a model that can be used for batch processing. Based on a TIF file of positive openness with a kernel size of 5, a model was created, which is visualised in figure 2. It is quite simple model in which the feature extraction is run twice. The first run is based on the training set. The second is run on the results of the first run. A final step is a smoothing of the outcome of the second run. The applied approach proved useful and the automatic extraction model showed to be time gaining, although still manual adjustment has to be done to create a complete network.
There exists another extension of Features Analyst, called Road Tracker. This promising extension of the former GeoEye (now Digital Globe) is not sold anymore. Nevertheless, after contacting the company, they were willing to do some tests. Unfortunately, the automatic or interactive tools didn´t pick up the linear features. However, it remains an application that merits further investigation. The issue of double lines instead one centre line, happens also with openness & FA (workflow 2), but with a much lower frequency and only with broader roads. This doesn´t constitute a problem as broader roads are easily depicted on visualised ALS data.

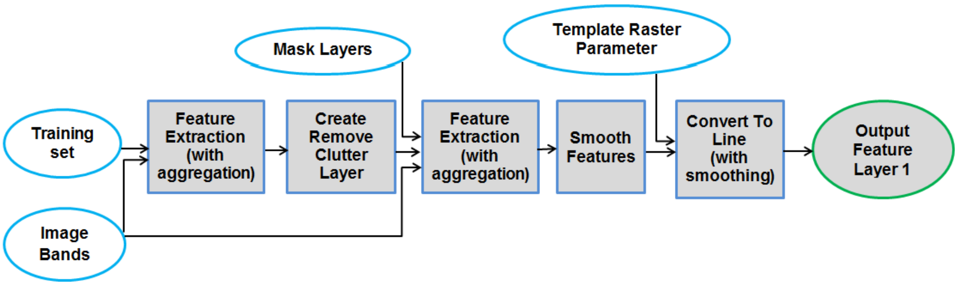
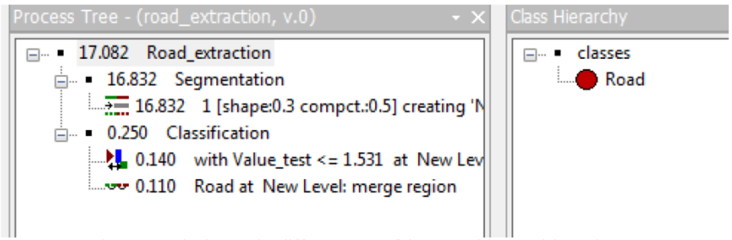


Figure 2. The model created in Feature Analyst

In workflow 3 the extraction took place in eCognition. Nevertheless, it´s complexity, quite easily and fast a first model was built (figure 3). It consists out segmentation, classification and a merge step. A major advantage of eCognition is that objects can be selected on the basis of the pixel values. In this way you can set sharp threshold for the pixels, which you want to extract. Another advantage is that it doesn´t take a long time to run it over the tiff images (tiles) and batch processing is possible. The step to export linear features works well. However the lines result very wiggled. The reason for this is that lines are based on the skeleton of the object rendered in the software package. However, in ArcGIS a tool for smoothing linear features is included. This constitutes of course an extra elaboration step.



```
17.082  Road_extraction
  16.832  Segmentation
    16.832  1 [shape:0.3 compct.:0.5] creating 'N
  0.250  Classification
    0.140  with Value_test <= 1.531  at  New Lev
    0.110  Road at  New Level: merge region
```

```
classes
  Road
```

Figure 3. In the image the different steps of the eCognition model are shown.

Although the results of the extraction of first three works workflows were satisfactory, they were not complete. Partly, because of the incapability software packages to extract all (small) linear features and partly parts of former roads and paths are missing, because they have vanished over time by erosion or by human interference. Therefore, the extraction of complete historical road and path networks in forested areas is for the time being semi-automatic. Consequently, a

following up step will be the manual mapping of missing parts and connecting them. Comparing the three (remained) workflows, we can establish the difference in quality. The combination of openness and Feature Analyst, work flow 2; didn't face, or at least far less, the problems of “double lines” of workflow 1 (STREX with break lines). Further, it doesn´t have neither the issue of creeks and roads, and different roads becoming one feature. Moreover, workflow 2 demonstrated less noise, smoother lines and better connectivity than workflow 1. On the other hand workflow 1 seems better capable of detecting subtle features. However, a lot of them are probably not a road or a path. Workflow 2 has smoother and longer lines than workflow 3 (openness & eCognition). Also workflow 1 has longer line segments than workflow 3. This workflow performs better regarding detecting of subtle features. Nevertheless, this is only a very small advantage. Therefore, regarding quality, workflow 2 is preferred over workflow 1 and workflow 3. In figure 4 the results of these workflows are displayed.
Regarding the extraction methods we can establish that the STREX method and the combined method of Openness and Feature Analyst have been intensively investigated. Nevertheless, there is probably room for improvement. This is even more the case for eCognition. This software package has a lot of functionalities and tools. A major drawback is the huge of amount of time needed to really get acquainted with its capabilities. Unfortunately time was lacking. However, the results obtained by creating a simple model make this package interesting.

Next to quality, time is of course an important issue. We can split time in processing time and testing time. With the latter is meant the time needed to get acknowledged with the software and to optimize the model or settings. It is hard to quantify the testing time, because it is difficult to measure. However, an estimation based on experience suggests that one needs at least a couple of weeks to get to know STREX. The same accounts more or less for Feature Analyst and OPALS. As stated, for eCognition is much more time needed, as it is less straightforward. The processing time of the different methods are shown in table 3. It shows clearly that STREX needs much more processing time than the other software packages. The time range of 78 till 84 minutes of STREX depends on which mode is used for selecting points. One can choose between a certain number around the point of interest or the points which fall in a certain window size around the point of interest. The latter option takes more time. Intensity (OPALS) needs less time, but the quality is not sufficient. The differences become more important as the number of tiles increases. The laser scan of the Leitha hills area exists out of some 190 tiles of 1 square kilometer. As time gain is a main reason for the application of an extraction technique it is clear that both Feature Analyst and eCognition stand out.
Combining the results of the quality of the extraction of the workflows with the processing time they need, we propose the combination of Feature Analyst and openness as a workflow for extraction road and paths from ALS data in forested areas. In the end we batch processed the model created in Feature Analyst. In less than one working day (8 hours) almost 12.000 km of linear features were extracted for an area of around 190 square kilometres, based on existing DTM´s. At least 90 % consists out of roads and paths.

Table 3. In the table the (aggregated) calculated processing time of the four workflows are shown for a forested area of 1000 x 1000 meters (1 tile) in the Leitha Hills (Austria).

Time	**1.**	**2.**	**3.**	**4.**
Data Format	LAS	LAS	LAS	Full wafeform
Preprocessing	-	DTM (SCOP++) 16 Min.	DTM (SCOP++) 16 min	OPALS
Visualisation technique	Break Lines (STREX)	Openness (OPALS) 1 min.	Openness (OPALS) 1 min.	Intensity (OPALS) 8-9
Extraction software	STREX/ SCOP ++	Feature Analyst 1-2 min	eCognition 1-2 min	Estimated 1-2 min
Total time	**74-84min**	**19 min**	**19 min**	**9-11 min**

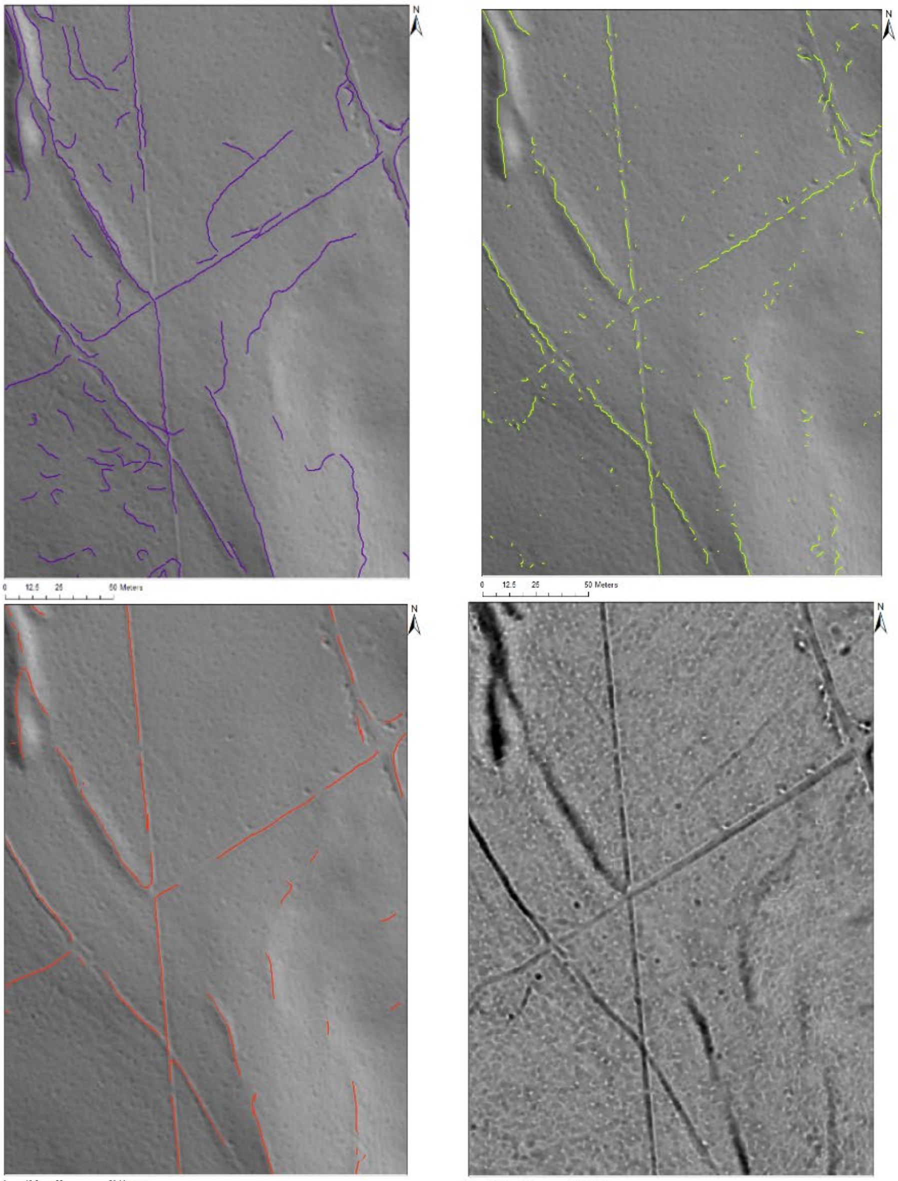


Figure 4. In the left upper corner the visualization of break lines (workflow 1) on a detailed SW hillshade image of the Leitha Hills. In right upper corner the results of openness and eCognition combination (workflow 3) on the same image. In the left lower corner the results of the combination openness and Feature Analyst (workflow 2) on the same image. In the right lower corner a positive openness image (kernel size 5) of the same area.

6 CONCLUSION

The huge amount of (archaeological) features that can be visualised needs automated extraction as manual mapping is very time-consuming and therefore costly. In this paper we compared four different workflows for automatic extraction. For the moment, workflow 2, which combines openness, for visualisation, and Feature Analyst, for extraction, proved the most worthwhile. Although, manual adjustment is still needed, this workflow for automatic road and path extraction has an enormous time and cost gain. This research could serve as a base for future studies regarding automatic extraction. Indeed, there is still room for improvement. Especially the software package eCognition looks promising as already good results have been obtained and its capabilities are not yet fully exploited.

ACKNOWLEDGEMENTS

I would like to thank the Technical University of Vienna for assistance and for allowing me to use their software (STREX, OPALS and SCOP++). The same accounts for GeoEye regarding the Feature Analyst plug-in for ArcGIS and for Trimble regarding the use of eCognition.

REFERENCES

[1] Mallet, C. and Bretar, F., "Full-Waveform Topographic Lidar: State-of-the-Art", ISPRS Journal of Photogrammetry and Remote Sensing 64(1), pp. 1–16, (2009).
[2] Doneus, M., and Briese "*Full-waveform airborne laser scanning as a tool for archaeological reconnaissance*", From Space to Place. Proc. 2nd International Conference on Remote Sensing in Archaeology, BAR International Series, 1568, 99 – 105, (2006).
[3] Humme, A, Lindenbergh, R and Sueur, C. "Revealing celtic fields from lidar data using kriging based filtering", International Archives of Photogrammetry And Remote Sensing, Volume XXXIV / 3A, pp. 295-30, (2006).
[4] Briese, C., "Break line modelling from Airborne Laser Scanner Data". Diss., Technical University Vienna, Austria, (2004).
[5] Doneus, M. a Briese, C., "Airborne Laser Scanning in Forested Areas - Potential and Limitations of an Archaeological Prospection Technique", in Remote Sensing for Archaeological Heritage Management, proc. 11th EAC Heritage Management Symposium, Reykjavík, Iceland (25-27 March 2010).
[6] Doneus, M., and Briese. C. "Digital terrain modelling for archaeological interpretation within forested areas using full-waveform laser scanning", Proc. The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2006).
[7] Djuricic, A., "Extraction of forest roads". Master thesis. Beograd. (2012).
[8] http://www.cbd.int/countries/profile/default.shtml?country=eur
[9] Briese, C., Mandlburger, G., Ressl, C. and Brockmann, H., "Automatic break line determination for the generation of a DTM along the river Main" Proc. Laser scanning 2009, IAPRS, Vol. XXXVIII, Part 3/W8 – Paris, France, (1-2 September 2009).
[10] SCOP++ Manual, Technical University of Vienna and INPHO GmbH (2010)
[11] Yokoyama, R., Shlrasawa, M. and Pike, R. 2002. "Visualizing topography by openness: a new application of image processing to digital elevation models", Photogrammetric Engineering & Remote Sensing Vol. 68, No. 3, p. 257, (March 2002).
[12] Doneus, M. Openness as visualization technique for interpretative mapping of airborne LiDAR derived digital terrain model, Remote Sensing, 5, (2013).

[13] http://www.geo.tuwien.ac.at/opals/html/ref_glossary.html#ref_gloss_intensity
[14] http://www.geo.tuwien.ac.at/opals/html/ModuleAddInfo.html
[15] http://www.geo.tuwien.ac.at/opals/html/ModuleRadioCal.html
[16] Pregesbauer, M. "Object versus Pixel – Classification Techniques for high resolution airborne remote sensing data" Proc. 10th International Conference on Archaeological Prospection. Wien, Austria, 29.05.-02.06.2013. 200–202. (2013)

Chapter 3 A workflow for (semi)-automatic extraction of roads and paths in forested areas from airborne laser scan data.

This article has been published in AARGNEWS number 50 in March 2015. The PhD student is the only author and thus the whole text is written by him. The article is not peer reviewed and it has been written after a presentation at the AARG conference in Dublin in September 2014. The article is a further elaboration of the first step of methodology.

A workflow for (Semi) automatic extraction of roads and paths in forested areas from Airborne Laser Scan data

Willem. F. Vletter[1]

In this article, I would like to present my PhD project and the first results achieved as shown at the AARG conference in Dublin in 2014. The PhD project was carried out at the Vienna Institute of Archaeological Science at the University of Vienna. It is part of the Initiative College ArchroPro in which the Ludwig Boltzmann Institute is also involved. The title of the PhD is *Reconstruction of prehistoric and historic road and path networks in forested areas through the application of Airborne Laser Scanning*. For this project we formulated two main aims. The first one, and most important, is the development of methodology for the use of Airborne Laser Scan (ALS) data for historical road networks research. The second one is the reconstruction of road networks in two case study areas. The reason to work with two case studies is that the methodology should be applicable in forested areas of different landscapes. In other words, it should not depend on specific morphology, vegetation or regional road and path type. Therefore the ALS data of one research area will serve to develop the methodology and the second to prove the validity of its application in a different landscape.

The first research area is the Leitha Hills, about 40 kilometers southeast of Vienna. It is an area of 190 km2 of mixed trees, mainly oak and beech, on a limestone soil. The highest point is 484 meters above sea level. The difference in altitude between this peak and the lowest point at the foot of the hills is about 250 meters. The ALS data from the Leitha area will be used to develop the methodology. The second area is the Veluwe area. It is a mainly forested area in the center of the Netherlands on a push moraine with sandy soils and extends over an area of about 1000 km2. The forest is a mix of deciduous and coniferous trees. The highest point here is 110 meters above sea level; the lowest point is almost at sea level. Both study areas have a time depth from the Neolithic till now.

Before discussing the methodology and the first results, I would like to address the issue of why we think it is worthwhile to investigate historical roads and paths. Historical roads and maps can provide important insights about the landscape and its use in the past both on local and regional scales. If we compare, for example, roads and paths on historical maps of different periods, it becomes clear that road patterns have changed over a relative short period as have the uses related to them.[2] This should make us aware that landscape could be quite dynamic in historic periods and probably even in prehistoric times. The same accounts for the effect of erosion and other natural decay processes in the landscape on archaeological features.[3] These two facts should make us cautious when we draw conclusions about landscape in the past based on the features that are still visible or detectable.[4] Despite the importance of roads and paths for getting insights of historical

---

[1] willem.vletter@univie.ac.at Vienna Institute of Archaeological Science, Univ. of Vienna, A-1190 Vienna, Franz-Klein Gasse 1, Austria +43-1-4277-404 75

[2] Aston, M. Interpreting the landscape. Landscape Archaeology in local studies. Fig. 23 (1985).

[3] Krizsanits, B., Horvath, M. Das Leithagebirge, Grenze und Verbindung p. 29 (2012).

[4] Aston, M. Interpreting the landscape. Landscape Archaeology in local studies. Pp. 153-54. (1985).

landscapes, in a lot of countries there is a lack of knowledge regarding historical roads and paths.[5]

Unfortunately, few remains of roads and paths are left in the landscape due to human intervention or natural processes. Normally they are best preserved in forested areas or in heathland. This is the reason to concentrate on these kinds of areas. ALS has proved very valuable in the research of archaeological features in forested areas. Indeed, is the only technique which can be applied in such areas, as it can detect `through` the leaves of the trees. Also, it can be applied on a large scale, which is needed if you want to do research on regional or interregional basis. Moreover, is very suited for historical roads research as they can extend over a many kilometers.

In the second place ALS data can be used to visualize very subtle linear features. This high level of detail is of course essential to trace historical roads and paths, features which often can´t be seen by the naked eye in the field. An example is given by a road in a wet heathland area on the Veluwe in figure 1. On the image of elaborated ALS data a straight line is visible running from Southwest to Northeast. This road is a Koningsweg (´Kings Road). This kind of road was built by Willem III at the end of the 18th century for mainly hunting purposes, like his monarchial colleagues abroad. On a normal air photo you are not able see it. In the field, we could only find it with the elaborated ALS image in our hand. Even on the map of the late 19th century it is barely drawn and certainly not as a continuous road. This not only demonstrates the power of ALS, but could also provide information of the historical map. On the one hand one could, for example, discuss the significance of roads and maps on the historical maps. On the other hand, it maybe tells us more about the use of this road. As mentioned, they were straight lines through the landscape. In other words, the morphology and the wetness of the landscape were not considered when they were built. It might have been that for these reasons they were not viable. Moreover, their intended function was not to connect villages to each other or a village with its surrounding fields. Maybe only limited use of the road was allowed.

The methodology proposed has four main steps. The first step uses a technique which enables the (semi) automatic extraction of roads from ALS data in forested areas. In the chronological model, the second step, the relative and absolute dating of roads and paths, is carried out. This is based on historical sources and physical characteristics of the found roads and paths. As only parts of networks survive over time, the third step will serve to predict where unknown road and paths would have been, taking into account the networks found and their morphology. In the final step, the spatio-temporal visualization of roads networks will be investigated, with a focus on their development. As mentioned before, after development of the methodology in the Leitha Hills, it will be applied in the second research area to test its validity.

In this paper I will deal with the automatic extraction step and give description of the research carried out and the results achieved. A more extensive paper on the topic has been already published.[6]

---

[5] Guttormsen, G.S. Transregional Historical Roads in Local Landscapes: Via Egnatia in Macedonian Greece, in Die Erde 138 1, Special Issue: Mediterranean Landscapes, p. 98 (2007).

[6] Vletter, W. (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas in SPIE proceedings Second International Conference on Remote Sensing and Geoinformation of the Environment (2014).

ALS data can be visualized in a way that a huge amount of linear features, and thus possible roads and paths, are visible. Instead of manual mapping, which takes a lot of time I tried to find a way to (semi) automatically extract them. For this, I compared four workflows on quality, time and costs. The workflows are shown in table 1.

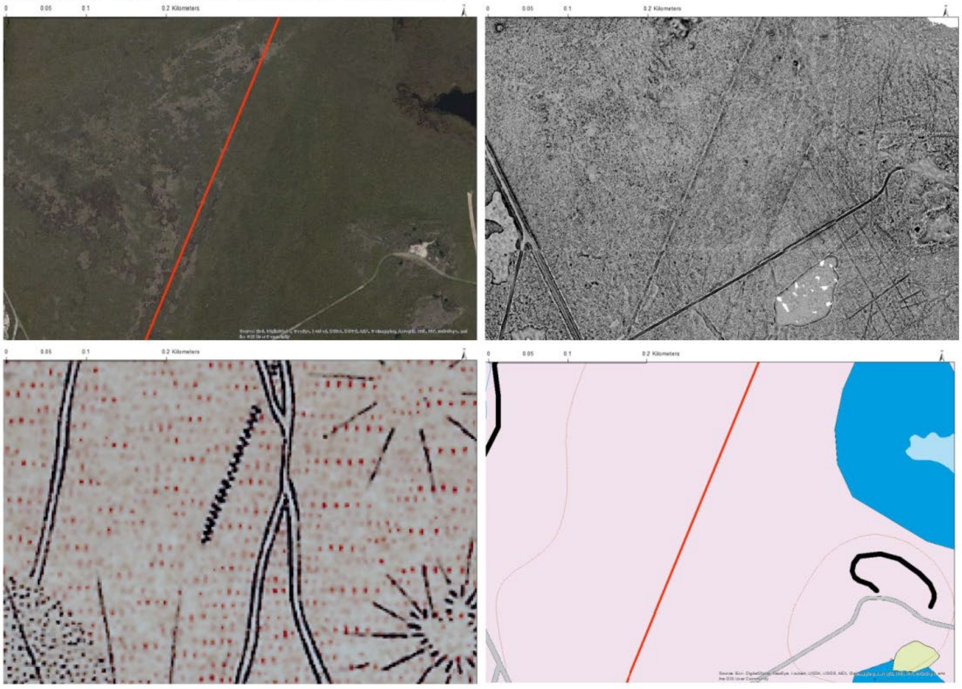


Figure 1. In the left upper corner the Koningsweg is shown in red on an air photo. In the right upper corner, the same road visualized with openness based on ALS data. In the left lower a historical military map from 1850. In the right lower is a geographical map in which purple stands for heathland. The water bodies in blue gives an indication of the wetness of the area.

	1.	2.	3.	4.
Data format	LAS	LAS	LAS	Full wave form
Preprocessing	-	DTM (SCOP++)	DTM (SCOP++)	OPALS
Visualization technique	Break Lines (STREX)	Openness (OPALS)	Openness (OPALS)	Intensity (OPALS)
Extraction software	STREX/ (SCOP++)	Feature Analyst	Ecognition	Feature Analyst / Ecognition

Table 1. The four workflows tested in this paper. For each workflow the data format, the (possible) pre-processing step, the visualisation technique used and extraction software are listed.[7]

---

[7] Vletter, W. (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas in SPIE proceedings Second International Conference on Remote Sensing and Geoinformation of the Environment (2014).

The first workflow is based on the concept of break lines. A break line is the intersection of two smooth surfaces, each surface interpolating the point on either side.[8] You can, for example, imagine that where a road or path lies deeper in the surface, that there is a break in the surface. For the break line concept the software package STREX was developed by Technical University of Vienna, which operates in DOS. It has 3 command lines. The structure line extraction tries to connect points from the point cloud that are situated at the same height and have the same orientation and creates small structure lines. The break line finder has the objective to connect these structure lines and create break lines. The final command line is a refinement step in which the results can be improved.[9] All three command lines contain parameters which can be adjusted; like, for example, the maximum angle and the length of the structure lines. In order to optimize the results, the software has been run a lot of times with different parameter sets. The outcome of the break line concept is shown in figure 2. As can be seen in this figure, STREX is able to detect subtle features as roads or small paths. However, there is a lot of noise, unwanted directions may be followed and also of double lines created for single linear features.

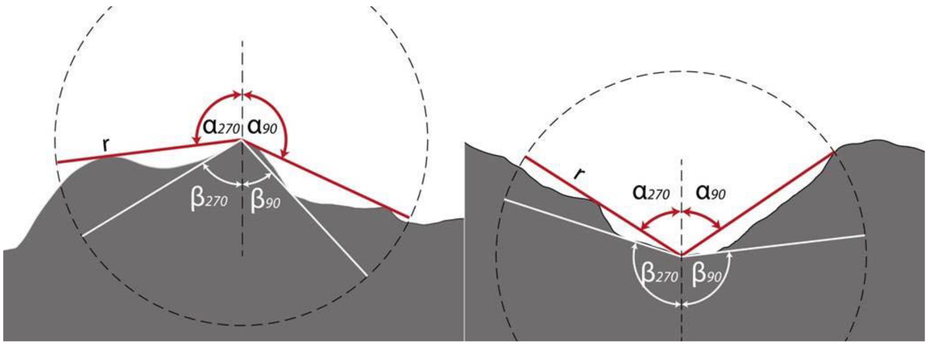


Figure 2. The visualization of openness shown in two directions. In left picture the positive openness in red has larger values than the negative openness in white. In the right picture it is the other way. The pictures also show that negative openness is not the inverse of positive openness.[10]

In the second and third workflow I applied the concept of openness to visualize the linear features. The reason for choosing openness as a visualization technique is that, from earlier research regarding visualization of ALS data of Leitha, it was considered best.[11] In general it can be stated that openness is well suited for the visualization of long linear subtle features like road and paths. Openness is defined as parameters expressing dominance or enclosure to visualize topographic character, or as an angular measure of the relation between surface relief and

---

[8] Briese, C., "Break line modelling from Airborne Laser Scanner Data". Diss., Technical University Vienna, Austria, p. 25 (2004).

[9] Briese, C., Mandlburger, G., Mücke, W., "Maßstabsabhängige Modellierung von Strukturlinien aus Airborne Laser Scanning Daten" in "Publikationen der Deutschen Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V., Band 19, p. 562 (2010).

[10] Doneus, M. "Openness as visualization technique for interpretative mapping of airborne LiDAR derived digital terrain models" in Remote Sensing, 5, p. 6429, (2013).

[11] Doneus, M. "Openness as visualization technique for interpretative mapping of airborne LiDAR derived digital terrain models" in Remote Sensing, 5, p. 6439, (2013).

horizontal distance.[12] Openness measures the mean of the dominance of enclosure of a certain point in normally eight horizontal directions. The angle with surface expresses the level of openness. We can say that positive openness is above surface and negative is below. L is the distance of how far is measured from a certain point. Looking at the angles in figure 2 it shows that if a point lays higher that its surroundings that the positive openness is higher and the negative openness is lower and vice versa. It also proves that negative openness is not the inverse of positive.

The following step in the second workflow was the extraction of the visualized linear features with the software package Feature Analyst, which can be plugged in ArcGIS and also Erdas Imagine. It can be used for different kind of imagery, like maps and satellite images. I used it also for historical maps and it works quite well. The most important step is probably the creation of the training set. Then the parameters have to be set. Once the software is run, the results can be improved or adjusted by using certain tools, like smoothing for lines. The final product is a model, which expresses all the steps you selected. Once you have created a model, based, for example, on a single tile, it can be run over the remaining tiles using batch processing.

The results of the combination of openness and feature analyst are quite good, although some parts are missing (figure 3). Compared with the break line concept of workflow one, it has far more less noise, less double lines, and less odd orientation.

In the third workflow, again openness was used but this time combined with Ecognition software. Ecognition is powerful software but it takes time a lot of time to know it thoroughly and to exploit its full capacities. Nevertheless, in a short period I managed to create a simple model, which involved segmentation, a classification based on pixel values and a merging step. The result was exported as a linear feature. As with Feature Analyst it is possible to carry out batch processing.

If we compare the results of work flow 2 with work flow 3 (Figure 3), it is clear that Ecognition may detect more subtle features, but they are less straight and there is more noise and the lines are more interrupted. The results in Ecognition can probable be improved by using image statistics in the classification step. However, this required more investment in knowledge of Ecognition which, unfortunately, was not possible at the time of the research.

Intensity was tested in the fourth workflow, calculating as intensity the amplitude multiplied by the Eco width of the laser pulse. With intensity, far fewer linear features can be visualized. This may probably be improved by calibration, but I suspect that the differences in the backscattering signal between a small path and its surroundings are still too small to be detected. This consideration, combined with difficulty to carry out a calibration on the short term lead to the decision to not further investigate the possibilities. So if we compare the quality of the workflows, openness combined with feature analyst performed best (Figure 3).

---

[12] Yokoyama, R., Shlrasawa, M. and Pike, R. 2002. "Visualizing topography by openness: a new application of image processing to digital elevation models" in Photogrammetric Engineering & Remote Sensing Vol. 68, No. 3, p. 257, (2002).

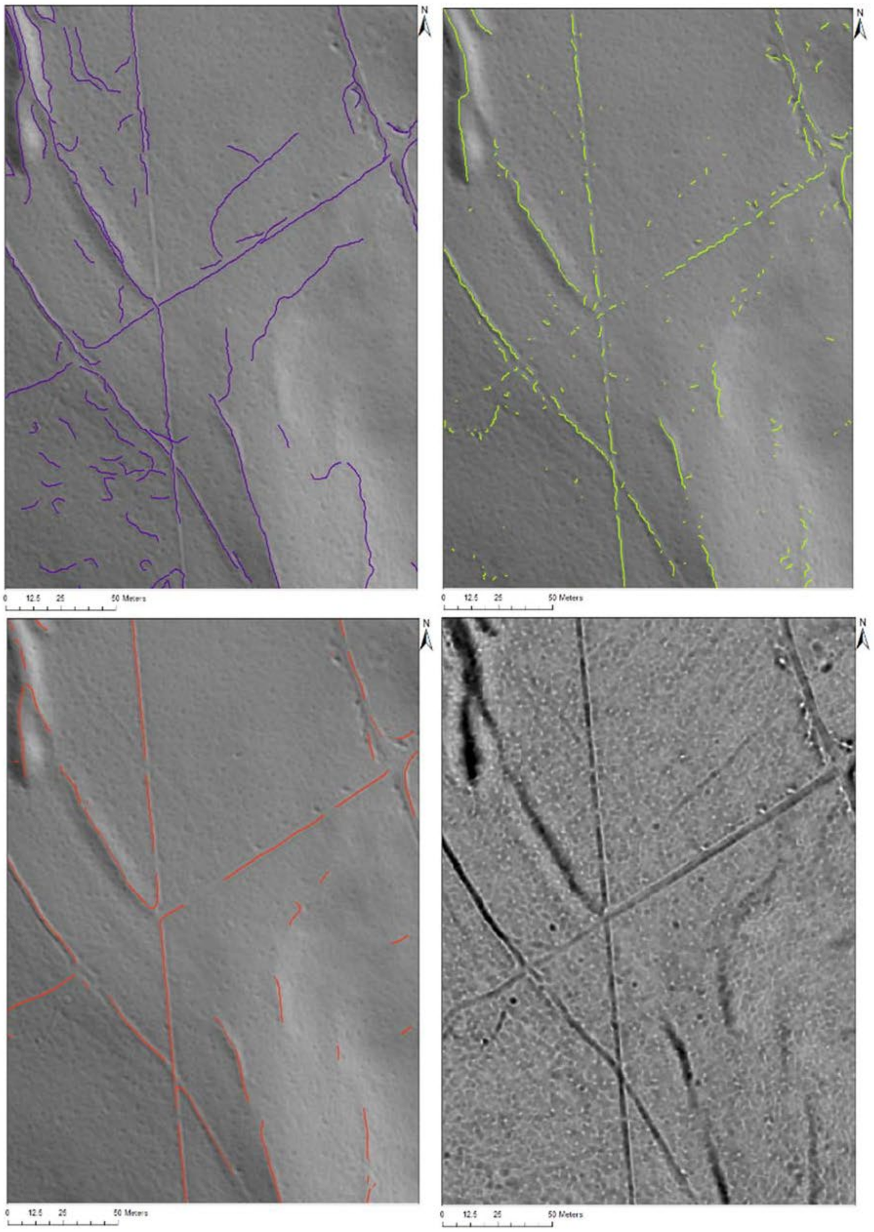


Figure 3. The same SW hill shaded ALS image of the Leitha Hills is used to show results from different workflows. In the left upper corner the visualization of break lines (workflow 1). In right upper corner the results of openness and Ecognition combination (workflow 3). In the left lower corner the results of the combination openness and Feature Analyst (workflow 2). In the right lower corner the positive openness image used (kernel size 5).[13]

---

[13] Vletter, W. (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas in SPIE proceedings Second International Conference on Remote Sensing and Geoinformation of the Environment (2014).

Also, the processing time for a tile of 1 square kilometer for all the four workflows was calculated. The intensity option delivered a processing time of around 10 minutes. The processing time for the second and third workflow was similar about 15 minutes. The break line option of workflow 1 took at least 5 times more time than the workflows with openness.

Looking at the costs, we can tell that the STREX software for break line extraction is not for free on the market. However, the goal is to integrate STREX in OPALS, which is free for PhD students. Feature Analyst has 10 days free license. This is sufficient if you want built model. Especially, if you first study the manual. Often the company (Overwatch) is also willing to extend the free license. Ecognition is on the contrary quite costly. However, there is place for negotiation and for scientific purposes there is a discount. Taking into account the results, processing time and costs workflow 2 clearly is the best option for the moment.

In the end, this workflow was applied to the whole of 180 square kilometers area of the Leitha hills. It resulted that in less than two days, 300.000 linear features with a total length of 12000 km were extracted (see figure 4). Looking at them in detail, a first estimation leads to the conclusion that more than 80 % are segments of a road or a path. The applied workflow has resulted in a huge time gain.

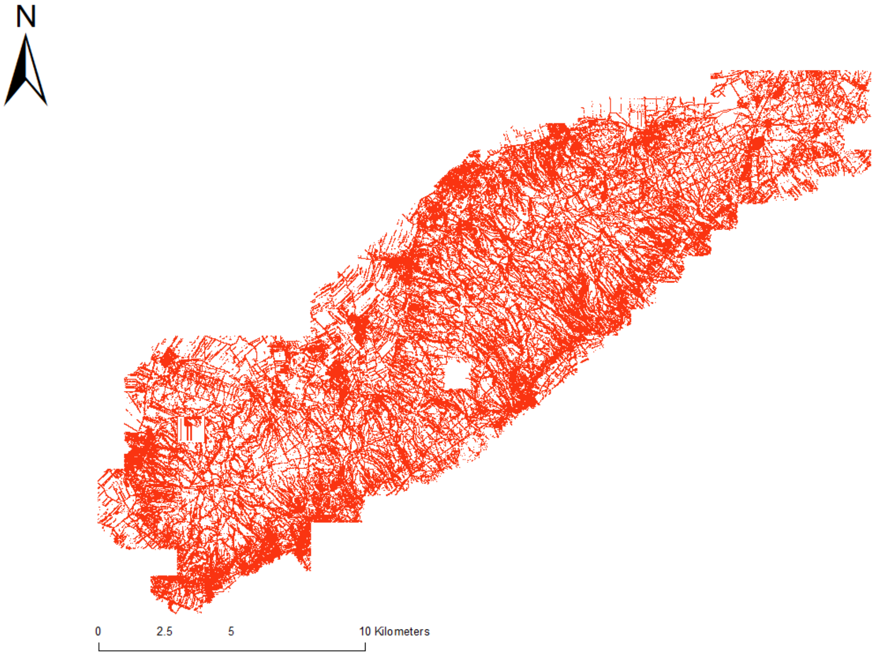


Figure 4. The result of the automatic extraction of linear features in the Leitha hills with workflow 2, which combines Openness with Feature analysts. In less than two days, 300.000 linear features with a total length of 12000 km were extracted of which more than 80% is estimated as being a road or a path segment.

---

ex

For the sake of clarity I would like to stress that automatic extraction is by no means interpretation. Nevertheless, it creates circumstances that allow more time to be spent on interpretation, which is often an issue with remote sensed data. The actual interpretation in this project will be dealt with during the (relative) dating in the chronological model of the methodology, where historical resources and the physical properties are taken into account.

Further, the networks in figure 4 are not complete. This is due to two main causes. On the one hand, for different reasons the software applications didn´t manage to capture all the linear features. On the other hand, sometimes parts of road or paths networks didn´t survive the wheel of time. The issues which come along with completing a network, both manually and automatically, are dealt with in a next paper. This also accounts also for the other steps of the methodology for reconstruction of prehistoric and historic road and path networks in forested areas through the application of Airborne Laser Scanning.

Chapter 4 Extraction issues.

This chapter is an intermediate chapter that gives insight on the issues which occurred during the extraction step. Possible solutions to solve these issues are discussed. This content is not intended for publication. The PhD student is only author.

4. Extraction issues.

The issues encountered following the automatic extraction (Vletter 2014), can be divided in two groups, although these groups are intertwined. On one hand we have technical issues of the data and how it is dealt by the software. On the other hand, we have different kind of features and their particular outlook which have affected the visualization and therefore the need for automatic extraction has emerged. Both groups will be discussed below in following sections. First the unwanted outcomes are talked about in the first section. In the second section the results of tests and possible solutions are presented.

4.1. Unwanted outcomes

4.1.1 Vanished connections.

There are situations where roads, but mainly paths, having a dead end or only parts are extracted. The reason for this not only is technical but also because they have vanished over time. Sometimes, it is almost certain that a road or path continued in the past. In other circumstances it is more doubtful whether it continued and where the exact location might have been. Filling up these kinds of gaps becomes human interpretation. The gaps are left open, as in the methodology a clear distinction is preferred between extraction and interpretation. Later on, the results for connecting these parts automatically, are shown. One could also consider a classification in which the probability of connection is expressed. However, these are considerations to deal with later.

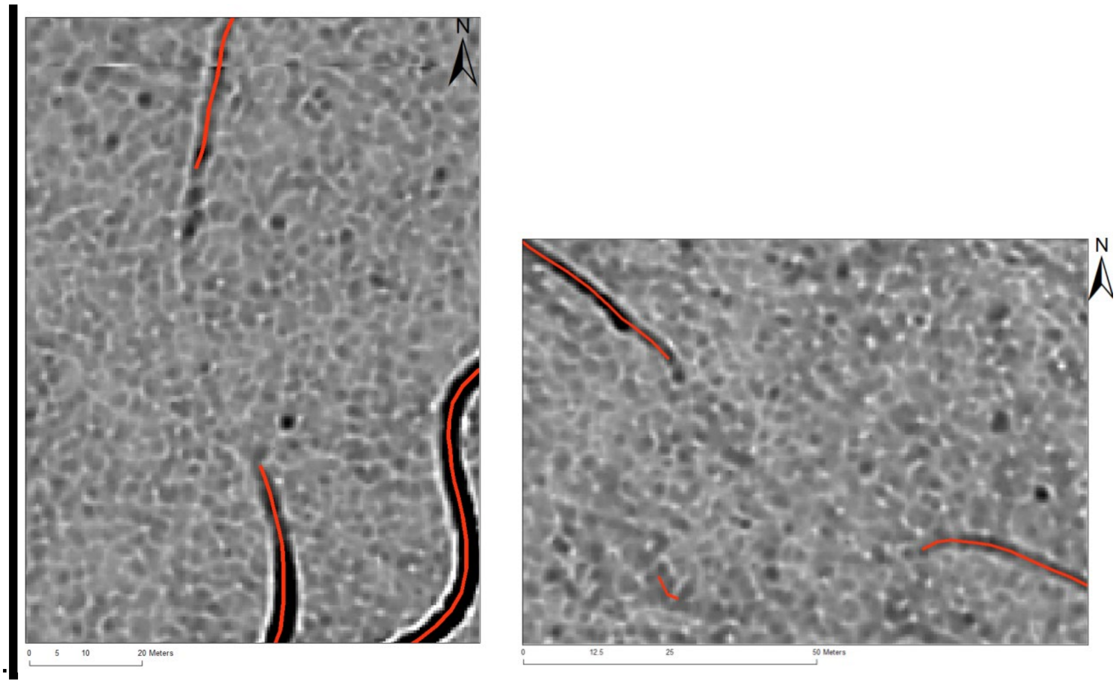


Figure 4.1a and b.

In the image 4.1a it seems obvious that the path coming from the North and the one from the South were connected. In 4.1b a connection between the two parts is less convincing. However, there is no (historical) evidence for in both cases that they actually did connect.

4.1.2 Double lines

One of the issues which came up is the extraction of gutters along a broad road resulting in the appearance of two lines for one road. The reason for this is the fact that the parameters were set to find small subtle linear features. Roads, particular modern roads, can be too broad to be extracted, but the gutters along is not. Instead of one central line you end up with two lines beside the road (See figure 4.2). It is very tempting to take one of these lines for representing the road, especially if it continues over long distances. However, it can lead to displacement of couple of meters of the centreline and can create problems at crossings with roads and waterways. Moreover, sometimes the gutter is part of a hydrologic system, so labelling it as a road would be incorrect. Fortunately, the case of double lines doesn´t occur very often. Therefore, it is preferable to draw manually a line at the centre of the road.

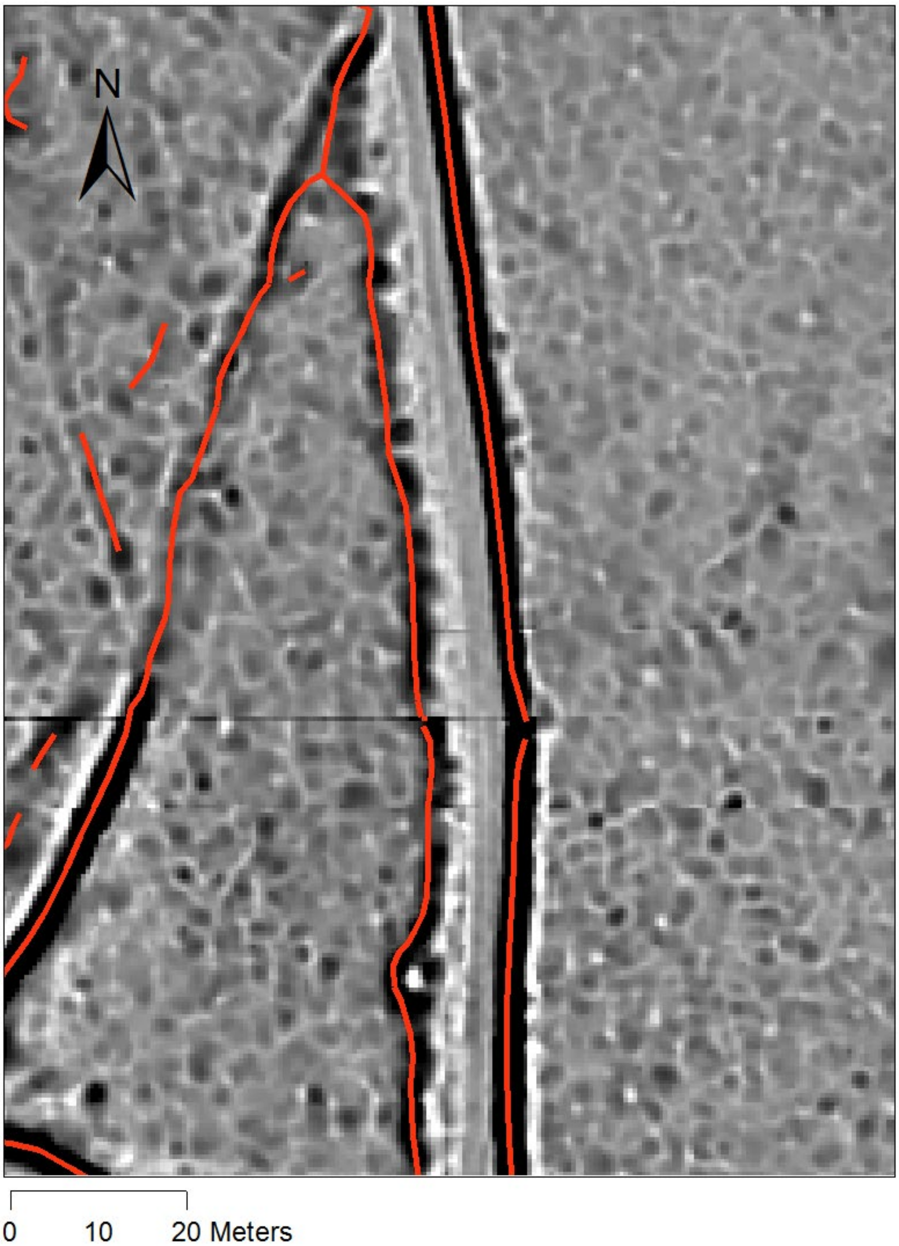


Figure 4.2 The gutters along road on the right side are extracted creating double lines.

4.1.3 Brooks.

Another issue is when, a road crosses a brook. As the software did not distinguish between roads, paths and waterways. The latter could become part of the same network. However, the brooks are in general well recognizable because of their shape existing out of short turnings. However, the brooks are not considered as noise. Their presence and outlook have influenced the road and path network. For this reason, they have also been documented. Nevertheless, in a following step they are disconnected from the road and path network. (See figure 4.3)

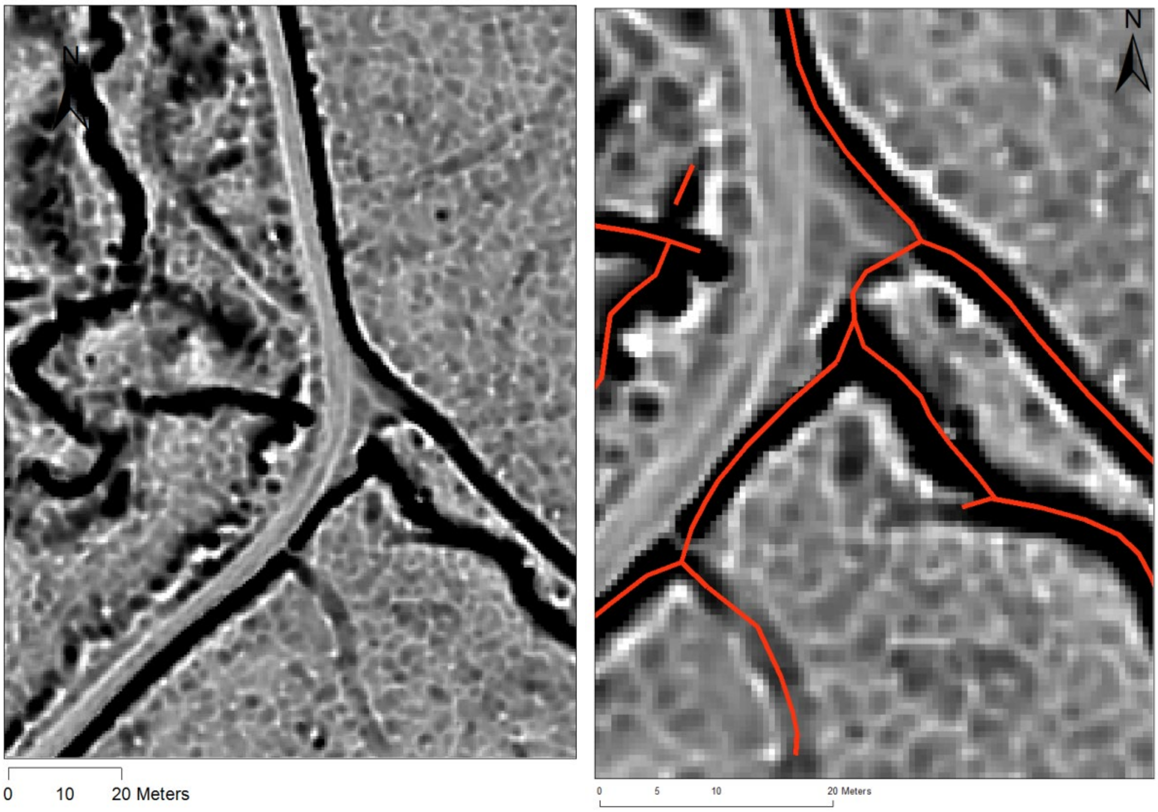


Figure 4.3 On the right side a close up of the image of the left side. Clearly a brook going under the roads is extracted.

4.1.4 Multiple track roads

Sometimes instead of one road or path it occurs that there exist a lot of tracks next to each other being part of the one and same route. One could consider to draw a centre line to represent this route. However, this distorts the picture of the historical roads too much and gives excessive scope of interpretation. The latter should take place in a next step. Especially, as Dietrich Denecke (1969) has shown that there exist different types of ´multiple track´ roads which have a different historical explanation, so valuable data would be lost. Furthermore, if a road in the past was not a single track but a more or less an open corridor, one cannot be too precise about its (pre-) historic course.Therefore, it was decided to use all the detected paths. Later they can be grouped together.

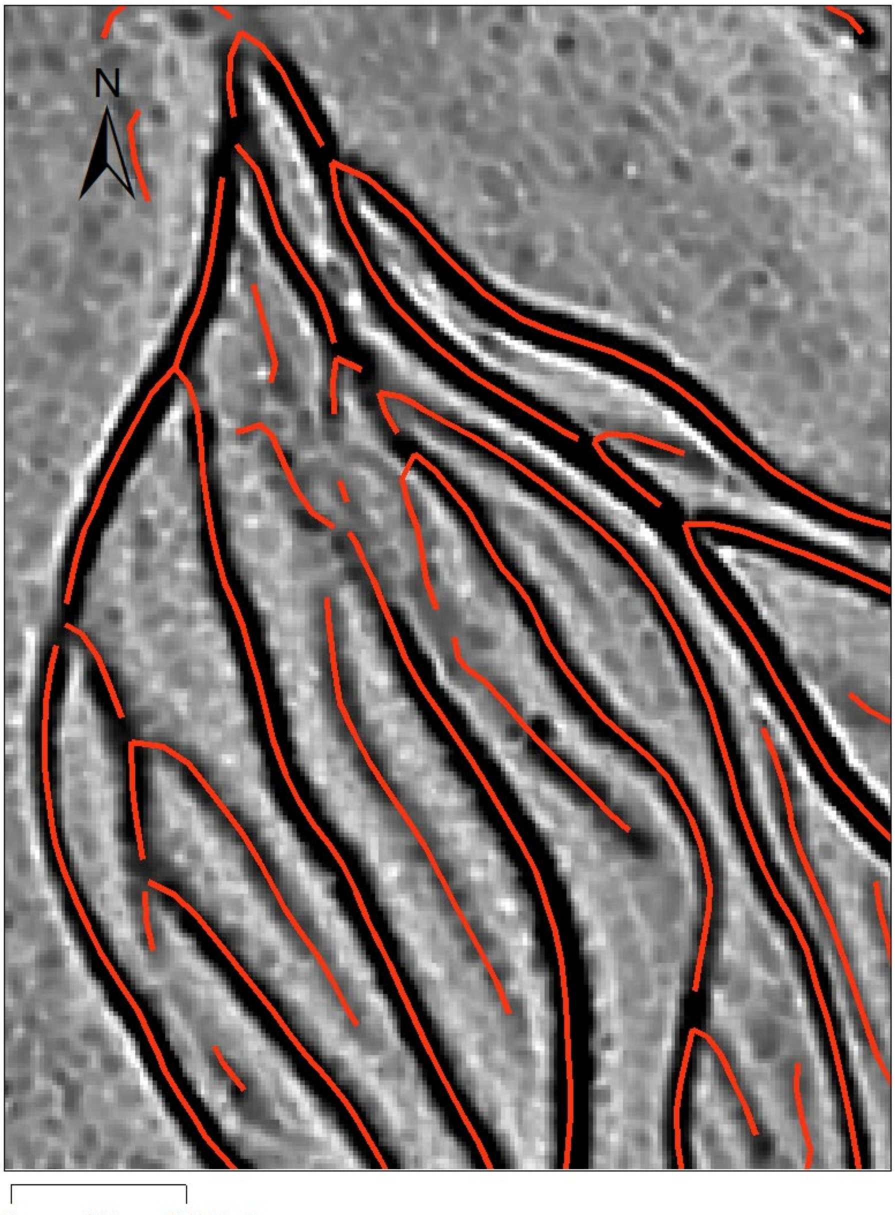


Figure 4.4 Multiple tracks

4.1.5 Agricultural areas

On the border of the hilly area, also the agriculture open land areas were scanned. They show a lot of linear features which are related to agricultural activity. The decision has been made to leave these areas out because the mentioned lines are not part of a road network. Moreover, roads in agricultural areas can often be better detected by other remote sensing techniques than ALS, like aerial photography. This does not mean that the Leitha hills road and path network is considered a closed network or not connected to any roads around it. On the contrary, in a following paper regarding the relative dating of roads and paths the connectivity to surrounded network will be taken into account.

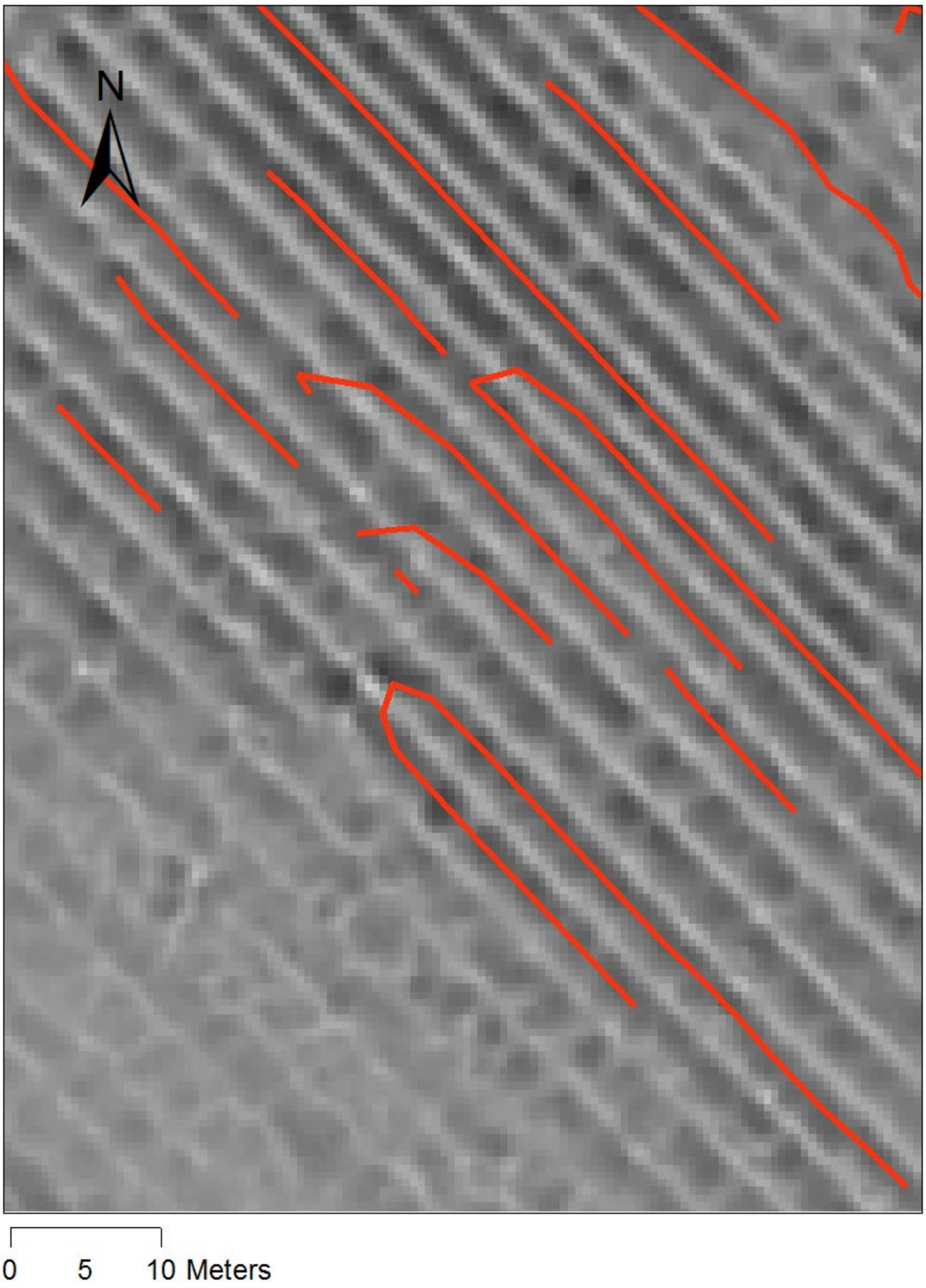


Figure 4.5 Agricultural features.

4.1.6 Modern forestry tracks.

On the ASL data a lot of modern forestry tracks can be seen. They are characterized by their width (almost 3 meter) which coincides with the overall width of modern forest machinery. The wheel tracks are often visible as they show a different tone in the grey scale of openness. Also, they make a lot of short turns, even circles, which do not make much sense as a road or path for travelling purposes. They are not present in the whole forest of the Leitha hills, as different parts are owned by different parties, which have their own manner of forest management.

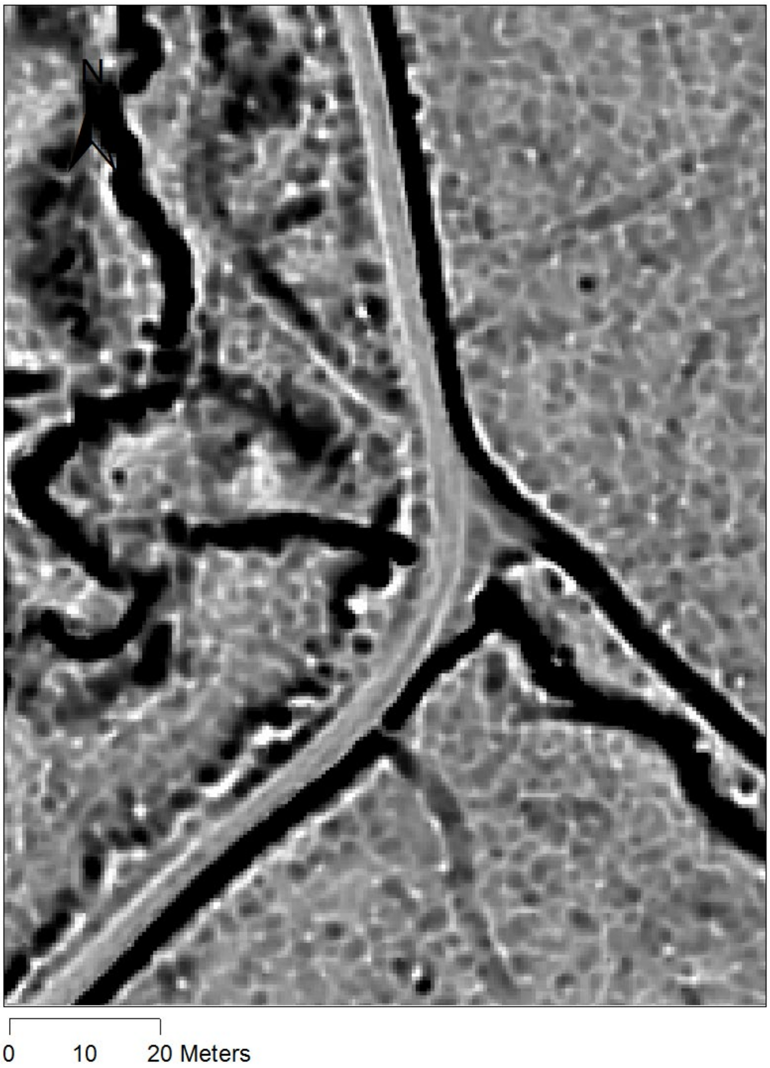


Figure 4.6 Broad modern forest roads.

4.1.7 Quarries.

Another type of features that were extracted are quarries. These are often easily recognisable. The quarries become interesting for the research if they have a long history. This could be of importance for dating the road leading to them.

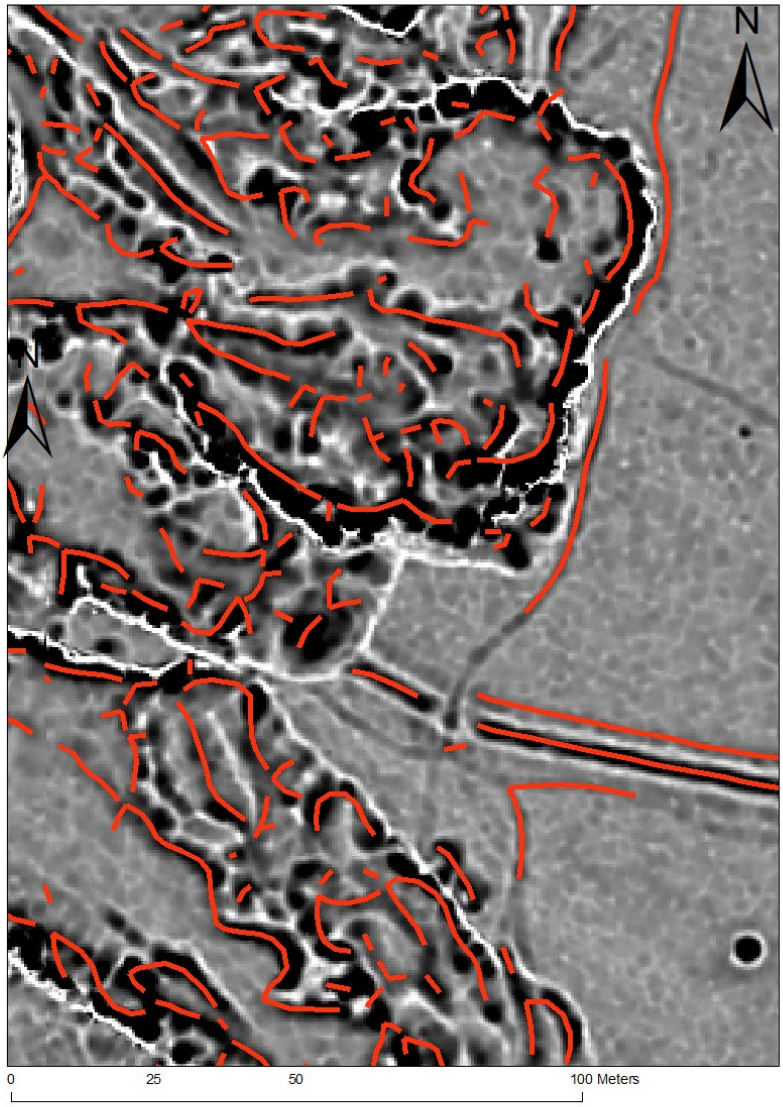


Figure 4.7 An example of quarries.

4.1.8 Border of tiles.

The division of the area in tiles is necessary for a manageable processing of the data for the software tools. Unfortunately, it also leads that on the edge of the tiles continuing roads and paths are interrupted. An improvement in the extraction model based on buffering an area around the tiles may avoid this problem in the future. For reasons mentioned earlier, some tools were tested to unite these and other loose parts of the network. The results are discussed in the next paragraph.

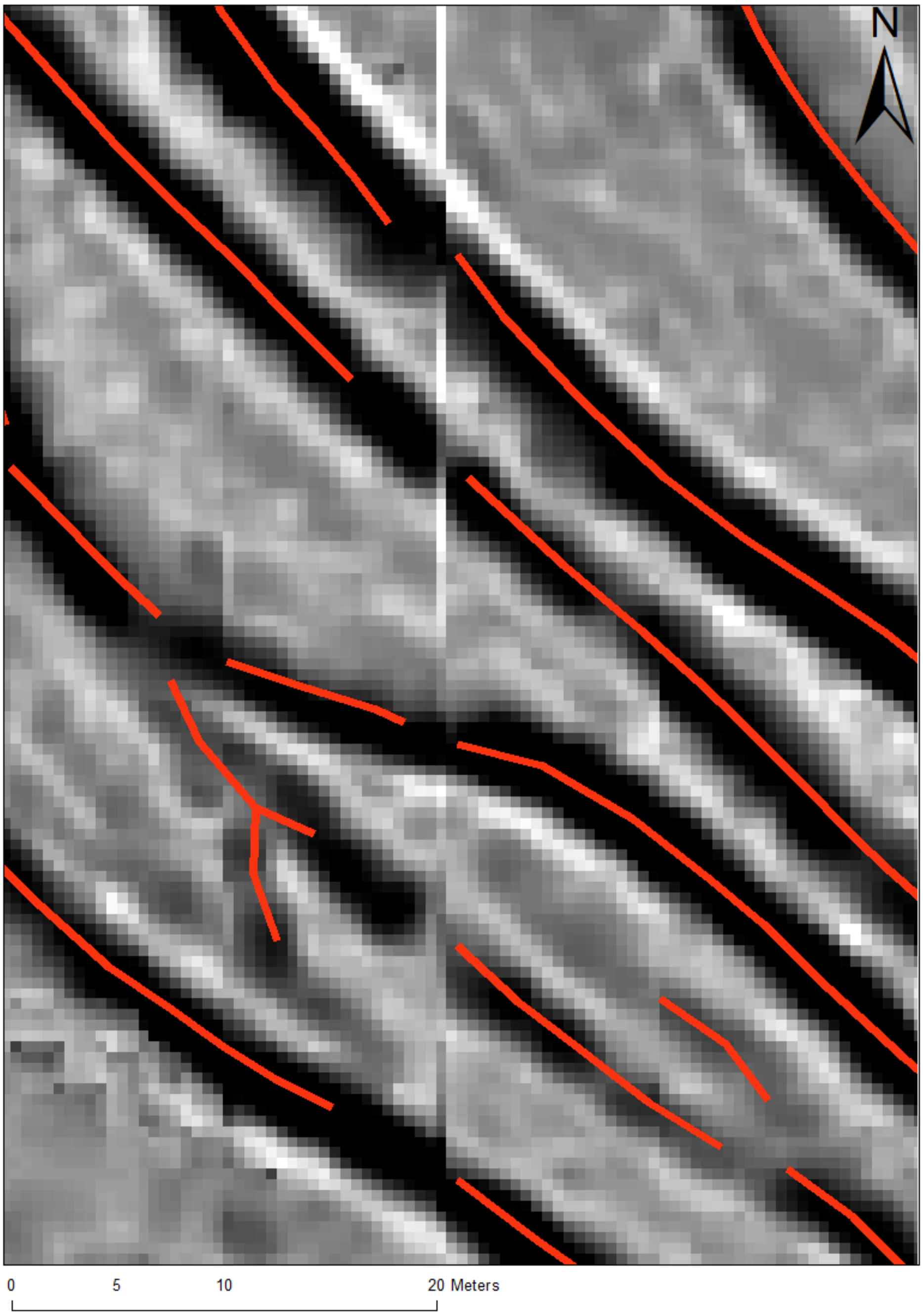


Figure 4.8 Discontinuing segments at the border of tiles.

4.2 Adjustments of unwanted outcomes

As mentioned before, the extracted networks were not complete and therefore several tools were tested to connect the extracted loose parts with each other, in other words completing the incomplete networks. Although in other software packages, like QGIS, there are tools to improve connectivity, among which among which only applications in ArcGIS were tested. On one hand, the reason for this is a lack of time to investigate the new software. On the other hand, and more importantly, is the doubt if the other packages can deal with huge data sets at the time of testing. In this paragraph the applied tools will be not explained in detail, as they are well described on the internet.

4.2.1 Topology rules

One of the most promising tools was topology and therefore we will start with the software application of Topology in ArcGIS. Topology derives from the Greek τόπος, "place", and λόγος, "study", the study of topological spaces. In geo-databases, *topology* is the arrangement that defines how point, line, and polygon features share coincident geometry.

In ArcGIS there exist a set of 32 topology rules which can also be applied in combination. An Important aspect about the rules is the minimal distance between two features (x,y tolerance). After several trial runs the best outcome can be found in figure 4.9. However, as can be seen the results are far from satisfying. New linear features were created which don´t match up with geomorphology and other illogical connections were made. Moreover, there is a huge loss of accuracy. In the end the results of application of topology are not very surprising as they are not created for adjustment for bulk data.

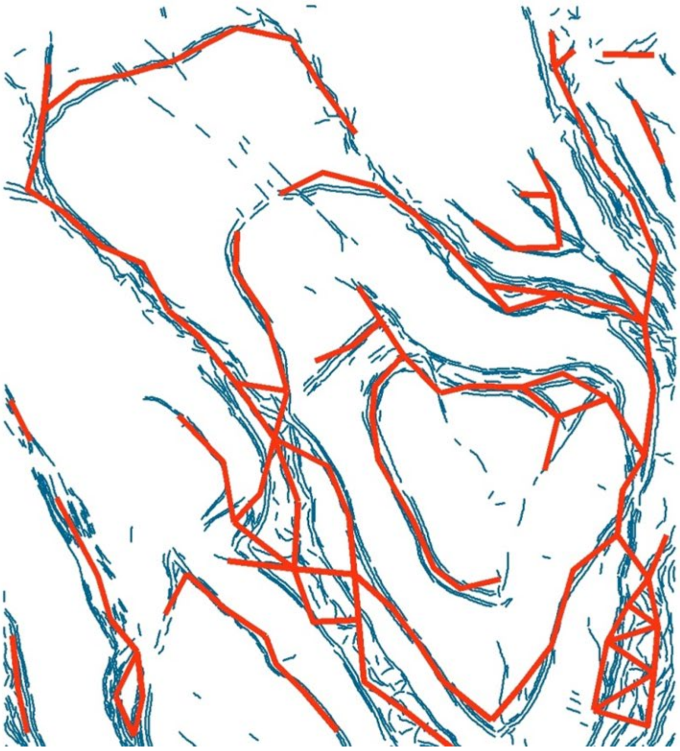


Figure 4.9 Result of applying topology rules for network adjustment.

4.2.2 Integrate

Integrate is defined to maintain the integrity of shared feature boundaries by making features coincident if they fall within the specified x,y tolerance. It is also suggested to complete incomplete networks. For this reason, the objective was to connect loose part of roads and paths. From the results in purple in figure 4.10 in becomes clear that this objective was not achieved. Indeed, more or less the same problems occur as with topology rules and the results were not satisfying as it links lines in a not logical way.

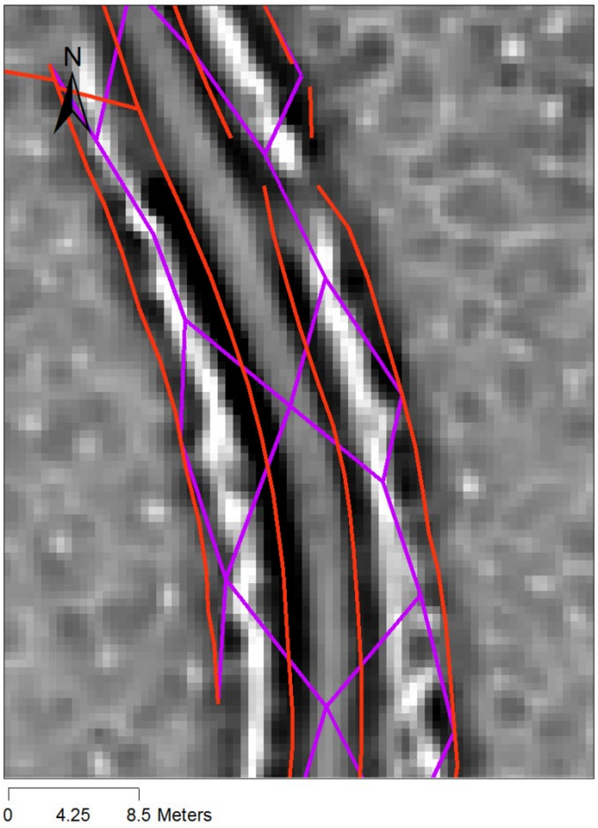


Figure 4.10 The result of integrate

4.2.3 Centreline

Another tool suggest by the ArcGIS users was centreline. By executing the following steps in ArcGIS. First “Feature to Raster” is carried out and thus making a raster file out of the shape file. Then with ”reclassify” a reclassification is carried out. Finally, with “Automatic Vectorisation” again a shapefile is created. This process looks quite cumbersome. However, within Python or another programming language these steps can probably written within one script. More important are the results of this application. As the outcome of both applications were far from satisfying as one can see in figure. 4.11

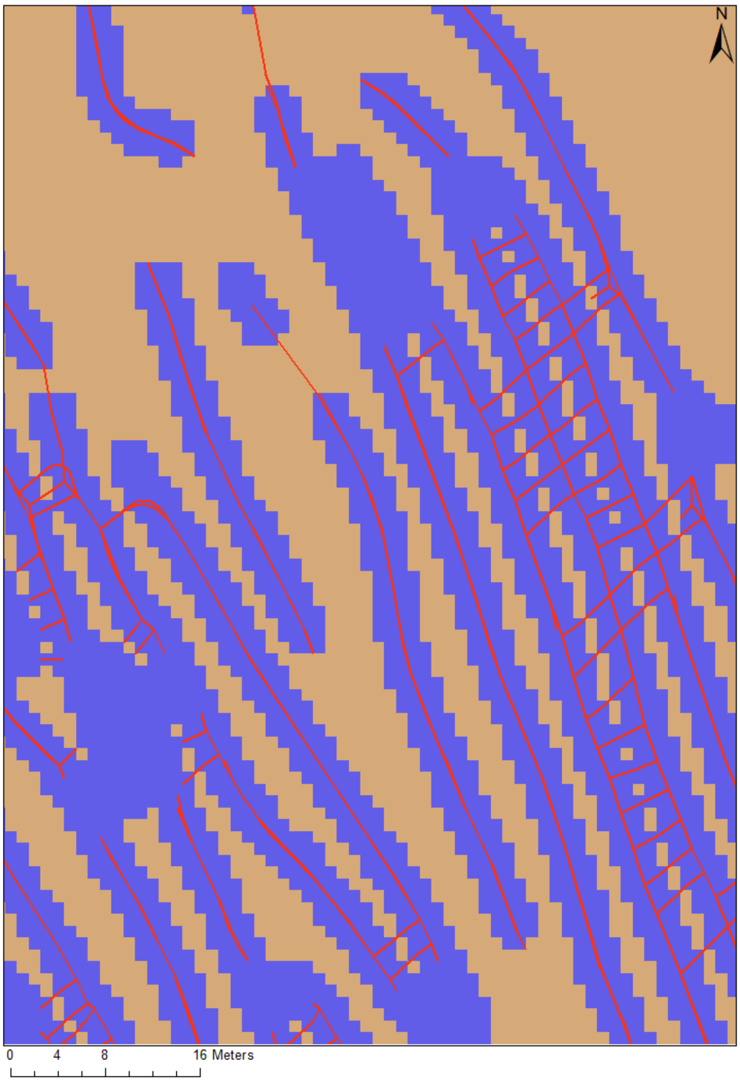


Figure 4.11 The result of centreline application.

4.2.4 Endpoint growing

A fourth founded option was endpoint growing of linear features by creating a buffer and making a centreline from the extended polygon and repeating this step over and over. In this test a combination of ArcGIS and E-cognition was used. As can be deducted from figure 4.12, this approach seems to work quite well. However, the combination of ArcGIS and E-cognition is quite time consuming as data has to be transferred manually. Besides, the software kept giving an error when carried out the intersecting step. This is probably due to huge amount of the data to be processed, which could be too much for the computer used (DELL laptop XPS). Therefore, a stronger computer might resolve the problem or the dataset should be divided in smaller parts. The latter solution would complicate the procedure. Another problem is that the end growing has to carried out by a couple of meters each time (a loop) in order to let it grow at the endpoints and to avoid connections laterally.

Possibly a lot of these issues can be solved by using Python, C++ or other kind of programming software. Unfortunately, this is outside the capabilities of the author. Engaging in this would probably take too much time and a positive outcome is not guaranteed.

In general, a major problem of the used software tools is that they ´think´ in two-dimensional way. In other words when connecting parts, they don´t consider the original morphology in which the roads and paths are situated. This also accounts for the non-visual gaps between roads. Therefore, it was opted to complete and adjust the networks manually, when needed.

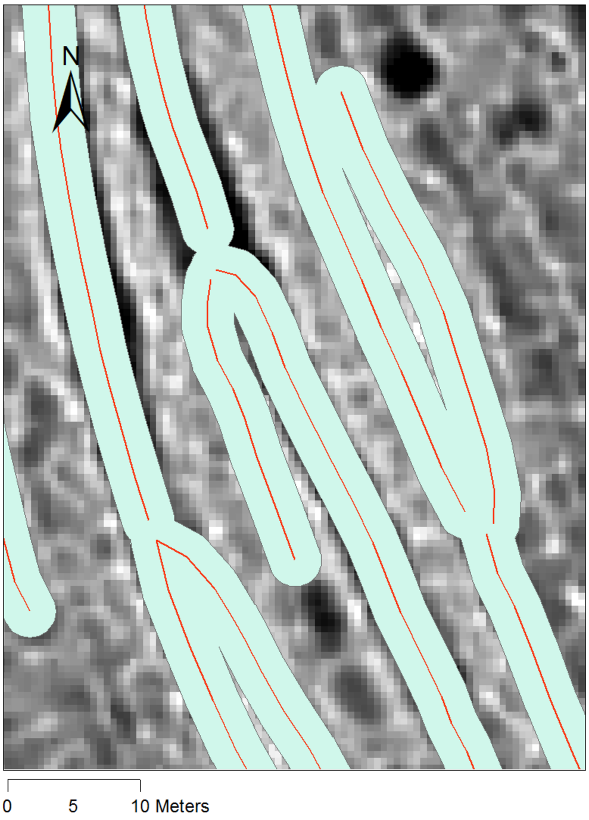


Figure 4.12 The result of end point growing.

4.2.3 Manual mapping

It can be concluded that the automatic adjustment of extracted networks did not yield in satisfying results. Therefore, still manual mapping is necessary for the parts that have loose ends, were not extracted or other issues in the extracted network. Mapping is itself a spatial process that involves negotiating various aspects of securing and maintaining the integrity of cartographic data as they circulate in space. As stated earlier, despite increased reliance on instrumentally measure survey, the human eye has remained a crucial element of mapping and the use of maps. With the capacity to transmit data instantaneously and manipulate it in real time on the computer screen, we have hugely increased the cartographic illusion of synoptic vision and action at a distance (the magic of maps). Of course, the only true map is the territory itself, as Louis Borges long ago pointed out. Therefore, it remains necessary to go into the field and to see how the features look like in their environment.

In this case the mapping is narrowed to possible archaeological features based on images derived of ALS data. As Michael Doneus (2013) has stated, that for mapping purposes, visualization techniques that “homogenize” archaeologically induced micro-topographic features and enable them to be clearly distinguished from the surrounding terrain become important. As mentioned before, based on such a visualisation, openness in this case, a large part of the road and paths is automatically extracted. In this step of automatic extraction, the focus lays on quality resulting in little noise. Therefore, the mapping exists mainly out of drawing lines between extracted parts.

Again, before the manual mapping, the software applications were more objective, as they treat the data in the same way. Now the human influence (experience, knowledge, state) is considerable. In the end manual mapping is always a kind of interpretation.

5 Conclusions

The automatically extracting of linear features from ALS data has proved useful, both in time and quality. Although the outcome is still not perfect and probably improvements can be made in the workflow. Therefore, it is worth wile to invest time into software applications for historical landscape research.

The automatic or semi-automatic extraction does not mean that the models created from laser scan data is not looked upon. On the contrary, just like with manual mapping visual inspection by the human eye remains important and necessary. Indeed, automatic extraction is by no means interpretation and the human agent will always be needed for this goal. One could say that automation can replace (partly) the physical part of drawing, but not the mental aspect of interpretation. When, like in this example, incomplete extracted networks cannot be completed automatically, manual adjustment should be carried out. One should bear in mind that the drawing of features will always represent a form of interpretation as it being done by humans with a certain knowledge and experience. Finally, one should remain aware that the data do not speak for themselves and other sources of knowledge should be investigated to interpret the data set and to understand the historical landscape.

In the following step of the methodology to develop, the (relative) dating of the roads and paths will be dealt with in a next publication. This is where the interpretation of the data will take place. In this way there is no mixing up of extraction and interpretation

References

- Denecke, D. (1969). *Methodische Untersuchungen zur historisch-geographischen Wegeforschung im Raum zwischen Solling und Harz. Ein Beitrag zur Rekonstruktion der mittelalterlichen Kulturlandschaft*. Goltze, Göttingen.
- Doneus, M. (2013). Openness as visualization technique for interpretative mapping of airborne LiDAR derived digital terrain models in *Remote Sensing, 5*, 6427-6442; doi:10.3390/rs5126427
- Vletter, W. (2014) (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas in. *Proc. SPIE 9229, Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014), 92291D (August 12, 2014); doi:10.1117/12.2069709*

Topic II – Chronological Models

Chapter 5 Creating a chronological model for historical roads and paths extracted from Airborne Laser Scanning Data.

This is a peer reviewed a chapter in the book „Digital methods and remote sensing in archaeology sensing.“ and is published in 2014. The PhD student is the main author and responsible of most of the text. The second author, Sandra Schloen, wrote most of paragraph 5.3. This chapter is the first of three chapters dealing with dating of roads and paths. The software application OCHRE is presented in this chapter as a tool for dating roads and paths.

Creating a Chronological Model for Historical Roads and Paths Extracted from Airborne Laser Scanning Data

Willem F. Vletter and Sandra R. Schloen

Abstract Chronological modeling is part of a methodology being developed for the use of Airborne Laser Scanning (ALS) data in reconstructing historical road and path networks in vegetated areas. It comprises four main steps. The first step tackles the (semi-) automatic visualization and extraction of linear features from ALS data. A model is presented in the second step to determine the (relative) chronology of historical roads and paths. The third step deals with the predictive modeling of unknown networks. The final step combines a 3-D environment with a time element, resulting in a temporal-spatial model of the road and path networks found. The (semi-) automatic extraction results of the first step are published in August 2014 in the proceedings of the Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014). Based on these extracted networks of the first step and additional manual mapping, the chronological model of the second step is created. The outcome of the model will be presented in this article. The chronological model makes use of both the Harris Matrix Composer (HMC) and the Online Cultural and Historical Research Environment (OCHRE). The latter is developed at the University of Chicago. This is a multi-project, multi-user database system that provides a comprehensive framework for diverse kinds of information at all stages of research. Both the HMC and OCHRE proved useful for creating a relative dating model for roads and paths, as resulted from the case study presented in this article.

W.F. Vletter (✉)
Vienna Institute of Archaeological Science, University of Vienna,
Franz-Klein Gasse 1, 1190 Vienna, Austria
e-mail: willem.vletter@univie.ac.at

S.R. Schloen
Research Database Specialist, OCHRE Data Service, University of Chicago,
1111 E. 60 Th St., Chicago, IL 60637, USA
e-mail: sschloen@uchicago.edu

M. Forte and S. Campana (eds.), *Digital Methods and Remote Sensing in Archaeology*, Quantitative Methods in the Humanities and Social Sciences,
DOI 10.1007/978-3-319-40658-9_18

Introduction

Historical roads and maps can provide important insights about the landscape and its past use on both local and regional scales. If we examine the literature for reference material, there is very little on the dating of roads. An exception is Wilkinson et al.'s article (2010) which combines a remote sensing technique (CORONA satellite images), field investigation (trenching) and micromorphology to investigate historic roads (hollow ways), in an approach similar to the current doctoral research of this article's author. However, besides the pottery found in the hollow ways, no absolute or relative dating techniques were applied in Wilkinson et al.'s study.

The fact that little investigation has been carried out to date roads and paths is of course not a surprise. Indeed, unmetalled roads and track ways are extremely difficult to date. They have no constructional material to aid interpretation; while artefacts are rarely present (Smith 2011). Indeed, it is often difficult to establish the age of most pathways, which preceded the introduction of paving in Europe in the late 18th century onwards (Horsten 2005). Exception being the paved roads built by the Romans.

The above-mentioned difficulties mean historical road research must be based on historical, archaeological and geographical investigation. Indeed, it should go much further than the recording of surface features. Phenomena which don't leave visible traces behind, such as the historical context of the road network, road connections and the volume of traffic itself, should be considered in the reconstruction (Denecke 1969).

Nevertheless, recent technical developments have created more possibilities to date roads and paths both relatively and absolutely. One possibility comes from Airborne Laser Scanning (ALS), a technique able to capture surface relief in very high resolution and visualize details which can't be seen by the naked eye in the field. This technique supplies the data on which the author builds a methodology for the reconstruction of historical road and path networks in his current doctoral research and is the main focus of this article. Issues concerning the extraction of roads and paths from ALS data as well as the completion of networks is discussed elsewhere (Vletter 2014). The PhD project has two study areas: the Leitha Hills in Austria and the Veluwe area in the Netherlands. The former area is used to base the methodology upon, the latter to test the applicability of the methodology in a completely different environment. Additionally, the applicability of relative and absolute dating techniques and their suitability for the case study areas is also considered below. While the results and conclusion of the dating method comparison are presented in Sects. A Case Study and Conclusion. However, before proceeding, a brief background description of the research areas and the project data will follow.

The Research Areas

The Veluwe

The Veluwe is a mainly forested area in the center of the Netherlands on a push moraine with sandy soils, which extends over an area of about 1000 km^2. The forest is a mix of deciduous and coniferous trees. The highest point here is 110 meters above sea level; the lowest point is almost at sea level. Due to melting of the ice coverage, there are presently many small (dry) side-valleys, where also most of the villages are located. The Neolithic period provide the oldest known artifacts on the Veluwe. The most visible archaeology comprises mainly Bronze Age burial mounds and, to a lesser extent, the Celtic field systems. From the Middle Ages onwards, the area has suffered from drift-sand because of de-forestation. At the beginning of the 20th Century it existed mainly out of enormous zones of heathland. Later in that century many areas have been reforested again. The Veluwe, typically for the Netherlands, has a moderate maritime climate. The ALS data covering the study area was made available by the Dutch National Board of Water management (Rijkswaterstaat) and it is completely free for the public. In a following paper, when the methodology will be applied to this area, the ALS data will be described in more detail.

The Leitha Hills

The Leitha Hills is a forested area of approximately 190 square km, 40 km south of Vienna, which rises between 200 and 300 m above the valley of the river Leitha. It is covered by a forest of mixed deciduous trees, mainly oak and beech with varying degrees of understory (Doneus and Briese 2010). Geologically, the Leiha Hills lie between the Alps and the Carpathians and link the two mountain chains. Due to fractions and subsidence, valleys were created. They also caused acidulous and sulphur containing water which came to the surface on fault lines. Also at least thirty caves have been documented. Where the hills meet the plain, the landscape is often characterized by heathland with unique vegetation. The south side of the Leitha Hills is favoured by the micro climate of the Neusiedler lake (Krizsanits and Horvath 2012).

The archaeological sites in this area, which have been detected mainly on the digital terrain model (DTM) derived from ALS data, are mostly medieval or post medieval. However, in summary, these include: four late Neolithic hill forts, several Iron Age hill forts, round barrows, building structures, stone quarries, hollow ways, medieval field systems, medieval border-markers (so called ‘Hotters’), hundreds of lime-kilns, military trenches ranging from the post-medieval period to World War II and a large number of bomb craters from World War II which have been interpreted (Doneus and Briese 2010). Visible remains of human settlements in the woods are

Table 1 The meta-information of the ALS data used in this paper

ALS-project	Leitha mountains
Purpose of scan	Archaeology
Time of data acquisition	March—12th of April 2007
Point-density (pt. per sq. m)	7
Scanner type	Riegl LMS-Q680i Full-Waveform
Scan angle (whole FOV)	45°
Flying height above ground	600 m
Speed of aircraft (TAS)	36 m/s
Laser pulse rate	100,000 Hz
Scan rate	66,000 Hz
Strip adjustment	Yes
Filtering	Robust interpolation (SCOP++)
DTM-resolution	0.5 m

ruins, decayed hunting houses or monastic buildings (Krizsanits and Horvath 2012).

The Leitha hills ALS project data were captured during a dedicated ALS flight undertaken for the "LiDAR Supported Archaeological Prospection in Woodland" Project (Doneus and Briese 2010). The most important parameters of the ALS data used in this paper are stated in Table 1.

Based on this ALS data, a semi-automatic extraction was executed. The extraction was carried in two steps. First the micro-topography was visualized in grey scale using the openness module in OPALS of the Technical University of Vienna (TU Wien). The second step was creating the extraction model in the software plug-in *Feature Analyst* (Vletter 2014). In a following step the networks were manually completed and some topology was carried out to check the quality of the networks (Vletter 2015). This resulted in an extensive network in the Leitha hills. However, the question of dating this network of roads and paths remained to be answered the possibilities of which are discussed in the next paragraph.

Absolute Dating

There are several methods to date absolutely. Here will discuss their applicability for both research areas. One method for age dating, namely radiometric dating will be excluded. The reason is that this method calculates in such large time scales, that it is of no use for the research.

Archaeomatic Dating

To know the possibilities are of archaeomagnetic dating we must gain knowledge of the principles behind it. Of importance for this dating technique is the Earth's magnetic field. This magnetic field is constantly changing both in direction and intensity. It is generally agreed that the magnetic field is caused by dynamo process within the Earth's liquid outer core. Around 80% of the field can be explained by imaging a bar magnet at the centre of the Earth and inclined at an angle of 11 degrees to the axis of rotation. The remaining 20% is caused by localised turbulence in the outer core (see Fig. 1). This is called the geomagnetic secular variation which makes archaeomagnetic dating possible. For archaeological dating it is the variation in the local fields which is most applicable. In order to exploit these changes and use them for dating purposes we first need to establish a calibration curve which describes the changes in the local field over the historical period. Because of the

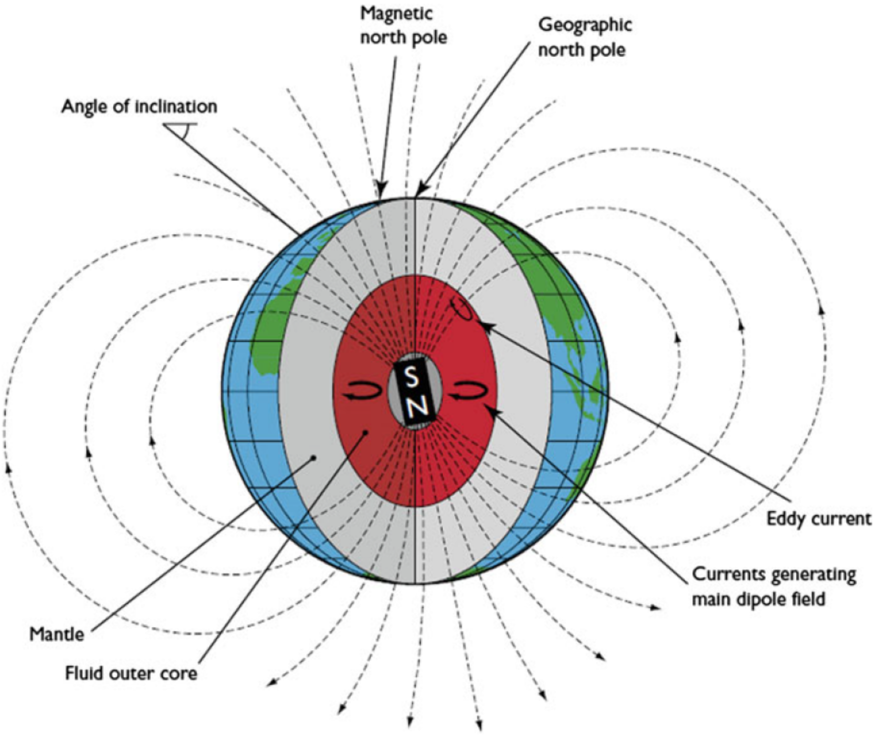


Fig. 1 The Earth's main dipolar magnetic field is depicted with dashed lines. This is generated by electric current circulation in the outer core (shown in *red*) and is similar to the field that would be produced by a bar magnetic located at the Earth's centre tilted off-vertical by about 11°, 5°. Eddy currents near the core/mantle boundary perturb this main field. The angle of dip (or inclination) is the angle that the field lines make with the horizontal plane where they cut the Earth's surface (USGS 2015)

random nature of the secular variation such a curve will follow no particular law and its shape will vary drastically from one part of the Earth to the other (McCann 2013). Hence, the archaeomagnetic dating strongly depends on the master Paleosecular Variation Curves (PSVC) used in the dating process and, accordingly, one must be careful in this respect. However, the problem of resolution and reliability in archaeomagnetic dating is difficult. The spatiotemporal distribution of the input database, the uncertainties within the database, its internal coherence and the technique used for modelling (classical PSVCs or global or regional models), define the resolution of the PSVC and, consequently, the resolution in archaeomagnetic dating. In addition to this, the relocation error introduces a bias in the dating process which is often not considered (Linford 2006).

Moreover, a feature and the conditions in which it is found, must satisfy to a lot of criteria before it can be used for archeomagnetic dating Nevertheless these obstacles, good results have been obtained. Therefore, it is worthwhile to examine it closer. As mentioned earlier archaeomagnetic dating is a physical dating technique that exploits the fact that the Earth's magnetic field changes over time. When structures such as kilns and furnaces are heated, the materials that they are built from can magnetise and record the direction and strength of the Earth's field at that time. Subsequent archaeomagnetic analysis allows these parameters to be determined and compared with calibration data to determine when the heating happened. Each time that the structure is fired, any previous magnetisation is lost, so the date obtained will be for the last firing. In some circumstances, archaeological sediments settling out from still water can also record the magnetic field at the time of their deposition and thus they can also be dated with the technique (Linford 2006). The rocks and sediments from which archaeological features are made contain trace amounts of iron oxides, which may be associated with the original rock-forming processes, or with secondary processes such as heating and weathering.

The main minerals are magnetite (Fe_3O_4), haematite (αFe_2O_3) and maghaemite (γFe_2O_3), where some of the Fe may be substituted by other cations (e.g. Ti, Al). Due to their ferromagnetic properties, they are capable of acquiring a remnant magnetisation in the presence of the geomagnetic field that is stable over archaeological (and geological) timescales (McIntosh and Catanzariti 2006).

Limestone, like in the Leitha hills, is a stone type which is usually not associated with iron minerals can often contain trace quantities of magnetic minerals capable of retaining a magnetic remanence (McIntosh and Catanzariti 2006).

Although, good results have been obtained, there are also difficulties with this method. For example wind and changed currents can have significant influence on the orientation of the magnetic field of sediment. It also indicates that palaeochannels and ox-bow lakes are ideal environments for successful archaeomagnetic dating, especially when the sediment has remained waterlogged since deposition. This means that suited sediments can meanly be found on and near lowland floodplain sites (Ellis 1998). This is not the case for the case-studies of the dissertation, which are both hilly areas. Maybe the Neusiedler lake, south of the Leiha hills, can be proper for this kind of research.

Another possibility for sediments are ditch infills. Here sediments may also may acquire a post-depositional remnant magnetisation (pDRM) at some time after their deposition, producing continuous records of directional (and occasionally relative intensity) secular variation (SV). The main drawbacks with sediments are that there is a delay in the acquisition of pDRM (related to the depth at which the pDRM is locked in and to the sedimentation rate), the amplitudes of SV may be smoothed and the values of inclination shallower than the actual field values. This can make comparison with archaeomagnetic data problematical. The key is in identifying the archaeological event associated with the remanence—such as the production of fired material or the last heating of combustion structures. In this respect, sediments are difficult to interpret as the age of magnetisation is normally older than the age of deposition and so it is hard to relate to an archaeological event (McIntosh and Catanzariti 2006). Moreover it is not clear if in the research areas proper road ditch infills can be found. Especially as ditches by preference have to be waterlogged and have had a slow accumulation of sediment (English Heritage 2006). This seems not be case for both study areas, where the inclination of the terrain is not suitable for waterlogging and slow accumulation (Fig. 2).

In the case of heated structures, the lime kilns of the Leitha hills and iron kiln of the Veluwe could be of interest. As roads and paths in hilly areas normally don't have datable structures, the age-dating should take place in an indirect way. The assumption is that archaeomagnetic dating of kilns along roads and paths provide

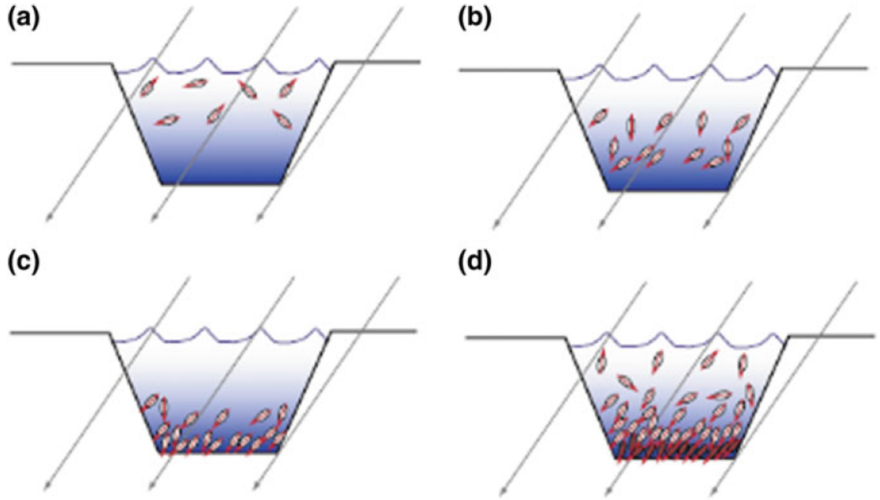


Fig. 2 Depositional remnant magnetisation. Sediment particle, each with a weak magnetisation, settle out of still water. As they fall through the water column they rotate to align their internal magnetisation directions with Earth's magnetic field (**a**, **b** and **c**). Once settled on the bed of the body of water, the weight of sediment accumulating on top of the particle locks them in place, leaving a layer of magnetised in the direction of the Earth's field (**d**) (McIntosh and Catanzariti 2006)

the age for which the roads and paths were (at least) in existence. However, it is skating on thin ice linking roads and paths to archaeological features on basis of vicinity, as there is no prove that roads and paths nearby have a relation with the kilns.

For the Veluwe (the Netherlands) there is another problem. At moment there is no good paleosecular variation curve. However there maybe the possibility to extrapolate the curve from Belgium or Germany to the Netherlands (McCann McCann 2003). In Austria Schnepp and Lanos established such a curve in 2006 (Pavón-Carrasco et al. 2011)

Optical Stimulate Luminescence (OSL) Dating

Luminescence dating is a form of geochronology that measures the energy of photons being released. In natural settings, ionizing radiation is absorbed and stored by sediments in the crystal lattice. This stored radiation dose can be evicted with stimulation and released as luminescence. The calculated age is the time since the last exposure to sunlight or intense heat. The sunlight bleaches away the luminescence signal and resets the time 'clock' (see Fig. 3). As time passes, the luminescence signal increases through exposure to the ionizing radiation and cosmic rays. Luminescence dating is based on quantifying both the radiation dose received by a sample since its zeroing event, and the dose rate which it has experienced during the accumulation period. The principal minerals used in luminescence dating are quartz and potassium feldspar (USGS 2015).

If we look at OSL we know that the presence of minerals and normally specifically quartz is needed. However, OSL can also be applied to (Volcanic) Feldspar and Potassium-Feldspar. We know that regarding the Veluwe the brown soil sand areas are relative rich of minerals. The less fertile white sands contain quartz (Berendsen 2008). These could indicate suitability for OSL dating. Of course the presence alone of quart z is not enough; also it should be preserved in excellent

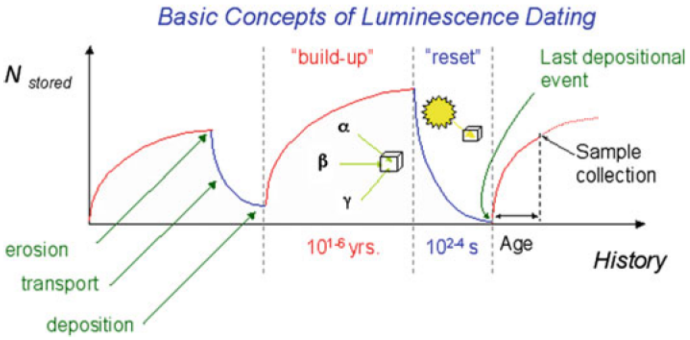


Fig. 3 Image produced by Dr. K. Lepper, North Dakota State University

conditions. Therefore, a closer look must be taken to really establish the suitability of these soils for OSL. For this reason and to gain valuable information of stratigraphy and soil data, in the spring of 2014 two trial trenches were dug across two different roads. In first case tracks were found and seven samples for OSL dating were extracted. An expert of the Wageningen University established that the samples are suitable for OSL dating. In the second trench another sample was taken from a road (late 17th century) of which we know the building date. In this way we have a check on the reliability and perhaps it could be used for calibration. The outcome of this research will be published in an upcoming paper.

The Leitha hills look at first sight not very suitable for OSL dating. Although, in some areas, like in Winden, quartz formation is surfaced, most of the soils are lime soils. The Trockenrasen ("dry lawns") may indicate the general lack of minerals in the area. However, only an investigation in the field could establish the real possibilities.

Carbon-14 Dating

The occurrence of natural radioactive carbon in the atmosphere allows archaeologists the ability to date organic materials as old as 50,000 years. Carbon-14 is continuously produced in the atmosphere and decays with a half-life of 5,730-year (+/− 40 years). Unlike most isotopic dating methods, the carbon-14 dating technique relies on the progressive decay or disappearance of the radioactive parent with time. This is now a common method for estimating the age of carbonaceous archaeological artifacts. The radioactivity of an artifact's carbon-14 content determines how long ago the specimen was separated from equilibrium with the atmosphere-plant-animal cycle. The method is based on the principle that all plants and animals, while they are alive, take in small amounts of carbon-14 and when they die, the intake ends. By measuring the loss rate of the carbon 14, the age of the object can be established (Archaeology wordsmith 2015).

Radiocarbon is the most absolute dating technique used in the Veluwe area. It has to be stressed that the samples for radiocarbon dating come from soils that were fossilized in the past. This will probably not be the case for road and paths, which normally will have been used over a long time period. An exemption could be the roads that are covered by drift-sands.

Regarding the Leitha hills no C-14 dating is known. Neither is the suitability of the area. It seems that was mentioned for OSL in Leitha hills also accounts for C-14 dating in this zone. Especially, when the acidity of the soil is considered, this is negative for the conservation of organic material. Indeed, the soil condition is very important for Carbon-14 dating possibilities. Regarding roads and paths, the only ones which are good datable are the wooden roads (Bohlwege in German) and paths in bog and peat areas. Thanks to the excellent conservation conditions the woods of these roads can often be dated by both Carbon dating and Dendrology (Denecke 2007). The latter is more accurate, but is less often applicable (Brindley and Lantink 1998). Indeed, the carbon dating of wooden roads has changed interpretation of the landscape and its use. In the Netherlands, Northwest Germany, but mostly in Ireland a lot of them have been found (Sanden 2002). However, wooden roads in bog and peat land have their own complexities and issues, which are often closely related to the hydrological situation of the bog itself (Casparie 2001). Nevertheless, the building activities of long tracks in bog and peat areas may suggest long-distance routes in prehistoric times. This is especially the case for Ireland. It doesn't make sense that people only travelled long distance on more difficult trafficable soils like bog and peat or only in Ireland. Nevertheless, in most of the cases the substantial evidence for this long distance travelling is lacking. An exemption maybe the Amber route along the Leitha hills. However, also in this case it is not clear from which northern area the amber originated.

We conclude that the possibilities for absolute dating of roads and paths in the Veluwe and in the Leitha hills are limited. Suited road ditch infills or other kinds of sediments are not likely to be available because of the inclination of the terrain which hinders not only the sediments to be waterlogged but also the slow accumulation of sediments. The only possible archaeomagnetic datable structures are kilns both for the Veluwe and the Leitha hills area. In the case of Veluwe it concerns iron kilns used to make iron out of bog ore. Limestone kilns can be found in the Leitha hills. This would be indirect dating as a link is assumed between archaeological features (the kilns) and roads which pass near and along these kilns. However, this is a hazardous enterprise as a direct relationship between the features cannot be established. A further problem regarding the Veluwe is that until now no reliable Paleosecular Variation Curves are available. An advantage for the Leitha hills is that the limestone can often contain trace quantities of magnetic minerals capable of retaining a magnetic remanence. Therefore, it is important to follow future developments in archaeomagnetics, because maybe will become possible to date the compacted (limestone) soil floors of roads and paths in forested areas. C-14 dating is possible in both areas. Although the acid soils in the Leitha hills and the white sands of the Veluwe are not the favourable conditions. Especially, if we consider road and path tracks. In the next paragraph we will look at the possibilities for relative chronology between roads and paths

Relative Chronology

Beside the possibility of absolute, there are also ways to determine the relative chronology by examining stratigraphic relations at intersections, archaeology, old maps, geomorphology and relative pollen analysis. We will start here with the latter.

Relative Pollen Analysis

The study of pollen grains in soil samples from an archaeological site which provides information on ancient human use of plants and plant resources. This technique, which is used in establishing relative chronologies as well as in environmental archaeology, was developed primarily as a technique for the relative dating of natural horizons. Pollen grains are produced in vast quantities by all plants, especially the wind-pollinated tree species. The outer skin (exine) of these grains is remarkably resistant to decay, and on wet ground or on a buried surface, it will be preserved, locked in the humus content. The Veluwe has areas that are well suited for pollen analysis and the reconstruction of the historical vegetation (Doornebosch 2014). The pollen grains of trees, shrubs, grasses, and flowers are preserved in either anaerobic conditions or in acid soils. Samples can be taken from the deposits by means of a core or from individual layers at frequent intervals in a section face on an archaeological site. The pollen is extracted and then concentrated and stained and examined under a microscope. Pollen grains are identifiable by their shape, and the percentages of the different species present in each sample are recorded on a pollen diagram. A comparison of the pollen diagrams for different levels within a deposit allows the identification of changes in the percentages of species and thus changes in the environment. As a dating technique, pollen has been used to identify different zones of arboreal vegetation which often correspond to climatic changes. The technique is invaluable for disclosing the environment of early man's sites and can even, over and series of samples, reveal man's influence on his environment by, for example, forest clearance. The sediments most frequently investigated are peat and lake deposits, but the more acid soils, such as podzols, are also analyzed (Archaeology wordsmith 2015). In peat and lake deposits are not present (anymore) in both research areas. For the Veluwe podzols are known (McIntosh and Catanzariti 2006). Indeed in the Veluwe pollen have been used to date burial mounds (Bourgeois 2013). Like for radiocarbon dating, it is important that the sample come from soils that were 'fossilized' in the past. In the earlier mentioned trial trenches across the roads investigated on the Veluwe no pollen were found. For the Leith Hills there are no data known and the geomor-phological map gives.

Relative Dating Intersection

Based on the visualization of intersection linear structures, one can establish which has been latest and therefore should be considered as more recent. This has a lot in common with a stratigraphic sequence or Harris Matrix. This Matrix is the fundamental diagrammatic representation of time for an archaeological site. However it

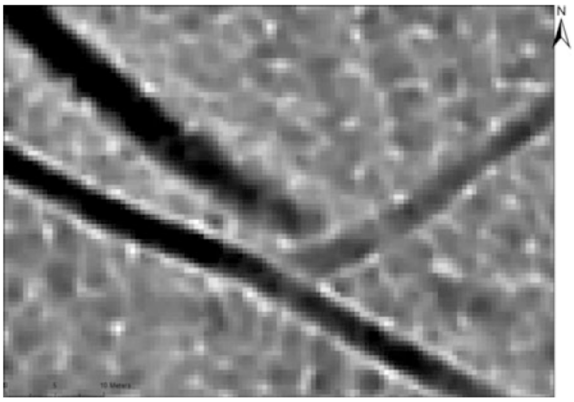


Fig. 4 It is clear from the image that the most southern Northwest-Southeast road is the youngest as it lies above the Southwest-Northeast road. The latter crosses clear the most northern Northwest-Southeast road, which is the oldest

can also be used for relative dating of roads. In the case of an archaeological site, it displays all uniquely numbered units of stratification in a sequential diagram, which represents their temporal succession. It provides the relative calendar which is the testing pattern for any further analysis. Its creation is based upon topological observations during the stratigraphic excavation process to deduce the stratigraphic relations. In historical road and path networks research, we can replace units of stratification by roads and paths and instead of excavation data we make use of elaborated ALS data to determine the 'stratigraphic relations'. The creation of a Harris Matrix does not consider any temporal relations that might be deduced from related finds in the subsequent analysis. They are used in the later grouping process of phasing or periodization by summarizing single units of stratification (roads in this case) due to structural relations or temporal relations (Schloen and Schloen 2012). In other words, the Harris Matrix can also be used to relative date roads and paths based on ALS imagery. Figure 4 gives a clear example of the visualization of an intersection in the Leitha hills of three roads.

Nevertheless, there are two considerations to make. A first consideration is the reuse or refreshment older tracks. If for example road A crosses over road B, it seems obvious that B is older A. This is true unless A is older but got out of use and came in use again after road B was established. This is theoretically possible. However the question arises in how many cases this really occurred. A second and probably major issue concerns crossings where it is no clear which road or path crosses over the other (see Fig. 7). This can have implications regarding the interpretation of the relative dating. For both the study areas good ALS are available to visualize the intersections (Fig. 5).

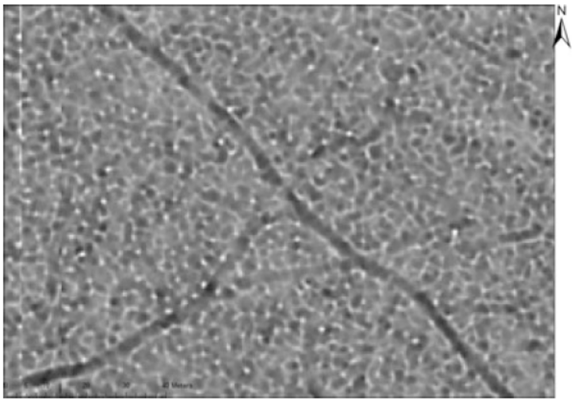


Fig. 5 The image shows the difficulty that can occur when to relative dating is based on intersection

Historical Maps

In the Leitha hills the large number of roads, tracks and hollow-ways are of special interest and some of them could be identified using old and modern maps (Doneus and Briese 2010). Indeed old maps can also provide an important indication of the era when a road or path is in used. It can be very tempting to consider a detailed historical map accurate and complete. However, there are some issues to be considered. Firstly, one has to deal with geographic accuracy of the road on the map. Especially, when more than one road lie near each other on ALS based imagery, it can be hard to discern which one is the oldest. In general military maps have a high degree of accuracy as the exact location of roads and other landscape features, like wet areas, were crucial for tactics. Further, more recent maps tend to be more precise.

Another aspect is the thrust worthy. It is quite possible that maps of certain period not reflect the real networks of roads paths that existed. When maps were based on older maps is possible, that roads were vanished over time and new ones not added. A simple reason for this would, that it was quite time and money consuming to do land survey and mapping the landscape. There are sufficient examples where roads are lacking or that towns are placed on the wrong side of a road (Aston 1985). As always with maps, it is important to know who made it and what was the purpose of it and in which circumstances it was made. In summary, one should take care when using old maps for dating for road or any historical feature. Nevertheless, they can provide valuable information. For both study areas we have good historical maps from the beginning of the 19th century, which demonstrate a high accuracy. For the Leitha hills also the (historical) hiking maps are of interest, like the one from 1922 (Krizsanits and Horvath 2012). Regarding the Veluwe already a lot information about main historical roads is gathered in an earlier research (Horsten 2005).

Archaeological Dating

Of course archaeological sources can help us with the dating. Nevertheless, also in this case there is an important issue to consider. If for example a road goes straight to a Neolithic hilffort, like in the Leitha hills, one is inclined to date this road as old (at least) as Neolithic. However, one should not date a road prehistoric because it runs along the hillfort or even to it (Hoskins 1988). In this case this Neolithic site was also used in the medieval times, it could be that this road is 'only' medieval and that the Neolithic road vanished in, for example, the Iron Age. A counter argument could be that roads are perpetuated when a site has a more or less continued occupation and the soil is not too sensible to erosion. Also site accessibility, as measured with the help of the modern road network, turned out to have as strong effect on the longevity. Cross-roads were found to be especially important in this respect (Leusen et al. 2005). Nevertheless, archaeological sites are important to imagine possible road networks. The original lay out of a village could tell us something about the landscape and it's use (Aston 1985). For this reason one has to consider the probable different organization of the landscape. For example, some areas in England demonstrated that in the Middle Ages there were no true villages. Most of the countryside was worked from single farm isolated in the middle of their own holdings. This had of course consequence for the communication ways. Thus when we consider the study areas we have to take into account that the habitation of the landscape and it's is use could be considerable different in the past. Indeed the picture of settlement development in the landscape is a dynamic picture of great complexity, great age and constant change, but we only see it at one time. Unless, we study villages, hamlets and farmsteads as dynamic, changing, developing entities, we will miss the significance of the form and the function of them when we see them at a particular date (Aston 1985).

Traces of religious activity could also provide information of landscape and its use. Forests and mountains suited of the Hermetic tradition well. The Religious landscape, more precisely the choice of locations for medieval monasteries was influenced by classical texts in their manipulation of the landscape, as well as by the hermetic tradition of Saint Augustine. Many monasteries were sited in loca-tions that might be described as rural retreats, and some evicted the residents of medieval villages in order to create these (Johnson 2008). Of course all the sites were connected by roads and paths to other places. Sometimes they were marked by objects along them. These "road markers" can tell us more about the age of the roads. One can think of mile stones, bridges and other buildings along a road. Archaeological research of these markers can deliver also import indications of the age of roads and paths. Looking at archaeological investigation in both study areas, we can see that lot excavations have been carried out for the Veluwe and little regarding the Leitha hills.

Geomorphology

There exist several processes that shape the morphology of the landscape. In relationship to the historical roads, only two of them are relevant for the study areas. Although, the Veluwe show clear traces of erosion of melting water, the erosion processes in Holocene have been quite limited (Bourgeois 2013). Of more importance have been the Eolic processes, the earlier mentioned drift-sands. The sands have covered up roads and also complete brooks. It caused roads to move further away, when the old track was covered by sand. This makes it possible to create a relative chronology of roads above and below the cover sand. However, it is in general very difficult to track back roads and paths covered by drift sand.

In the Leitha hills, where the slopes are steeper, a similar relative chronology can be carried out, but this time based on erosion. If for example one road goes over and landslide and another lays below it, it is possible to date them relatively. However, erosion plays also a role in the viability of the roads. It occurs often that a road or path turns into a small canal, especially after a heavy rain shower. At the moment there is no clear picture of the effects of erosion on historical roads and paths in the Leitha hills. Indeed, whilst it is easy to indicate which activities caused erosion, it is much more difficult to estimate the extent of erosion involved: the same form of erosion in one case may lead to utter destruction and in another case virtually no effect (Smith 2011). In the near future more insights into effects of erosion are expected to be gained in collaboration with the Technical University of Vienna.

A Case Study

The History of the Leitha Hills

Before to be able to date any road or path we should know about the history, and more specific, landscape history of this region. The origin of the name Leitha has different explanations. It comes from the old “Hochdeutsh” word “Litaha/ Lithaha. Probably it stems from Indo-Germanic root “loidh” that means as much mucus or slippery (Krizsanits and Horvath 2012). The Leitha hills have a history of the division. Nowadays and in the past it has been divided in the two different administrative units within Austria. The northern part is under the jurisdiction of Nieder-Östereich and the southern of Burgenland. This southern part has also been part of the Hungarian Kingdom. This history of division could be part of the explanation that little research has been carried which took the area as one entity. This explains also some of the roads as borders, like the “Grensweg” (Border road) between Mannersdorf and Hof am Leithagebirge. Sometimes boundaries followed a stream or a track way that already existed, but very often they created their own boundary lanes (Hoskins 1988).

The economic activities known, which have taken place through history in the Leitha hills are woodcutting, quarrying, cattle husbandry and communication ways for crossing the hills. The stone quarrying took place mainly on the border of the area. Probably because of logistic and costs matters. Along Leitha hills there was a cattle route from the Hungarian plane toward Vienna and further. On the maps there are still names that could refer to this period, like Groß Ochsenstand and Klein Ochsenstand. These areas are now wooded, but in former times there were open land. This could be an indication that in the past the Leitha hills was less forested in Medieval Times. For earlier periods the found Iron Age sites could be a sign that the hills were more occupied that in Modern History. However, this is not enough to suppose that during the Iron Age the area was more open.

Forestry took place in large parts of the Leitha hills and carts were used. It is interesting to see how the seasons influenced the viability in the Leitha hills. For example in autumn the falling leaves could make the roads slippery and dangerous. Besides used for economic purposes, the woods were used to hide. Indeed, people fled into the woods when Turkisch troops came to their towns. An example of a hiding place is the Teufelsloche (Devils hole) on the Sulzberg. They have in different periods protected people (Krizsanits and Horvath 2012). Interesting could be the roads or paths to these holes. Thirty holes are documented. The Hartl-Lucke is a good example. It was located near a gravel road, now it is completely overgrown. It also shows how fast places in the forest can change in only 20 or 30 years. This should make us cautious about reconstruction historical roads and paths. Moreover, we should remember that only a part of the historical roads and paths can be detected. Some holes have also served as hermitage.

The road names Brunnengasse or Quellengasse refers in a lot of places to the presence of a fountain or a well. Each town has such water well. Also other names demonstrate the former importance, like Waschgattl in Eisenstadt, where the laundry was washed or Rosschwemmen where horses were cleaned. In the Leinwandbleich the laundry was spread to bleach. Also the Ochsenbründl in Jois, named after the ones who pulled the carts through the vineyards, looked different in the past. It was like a swamp, where cows and geese came to drink from the nearby Hutweide. A Hutweide was for centuries the place were the animals of the local villages grazed. The animals stayed here during the summer and were protect by a shepherd or children from the villages. Here comes the name Hutweide from (behüten means protect). Each village had such a "Hutweide", normally between the village and the woods. The ground was too sparse to plant any crop. Often rocks and the slope made elaboration of the ground impossible. For the animals there was food enough. Drought resistance plants like hear grasses, which grow on both sandy and gravelly soils, were good enough for them. It was often an area between the village and the forest where the livestock grazed. It demonstrates again that the use and the outlook of the forest were different in the past. This is an important notion for interpretation of road features and reconstructing historical road and path networks.

One can find often traces of human live nearby the wells, which go back until the Iron Age. There was certainly a cult at these places. Often a link is made with the chapels to worship the Holy Radegundis, like in Großhoflein or Mannersdorf. Well pilgrimage took place which went back to pagan well worship. The Christian cult goes back till the 9th century in Leith hills (Krizsanits and Horvath 2012). All these holes, wells where connected to the towns with roads and paths. Therefore the archaeological record alone is not sufficient to reconstruct and understand the historical road networks. Knowledge of the geology and hydrology are also important. For this reason collaboration has been sought with the Technical University of Vienna.

In the forest near Eisenstadt there is a stone statute of Joseph and Maria. Maria looks in the direction of Eisenstadt and Joseph in the direction of Lorretto, symbolising the watershed (Krizsanits and Horvath 2012). The watershed could also be important for a ridgeway across the Leitha hills. The advantage of a ridgeway, which often date from prehistoric times, is of being dry, because of the water running down on both sides (Berendsen 2008). If we look at the Medieval border stones (Hotters) we can notice that they follow for a large part this watershed together with a road.

It can happen that in the forest that the water at some places gathers, where the ground is not permeable. These places are called locally "Wildschweinlacken", meaning wild boar pools. Indeed the boars wallow in these wet areas. Another example is the Saubründlegraben in the area of Stotzing. There are about 80 graben (trenches) in the Leitha hills. Their name are often derived from landscape features, but also to the owners. Some of the brooks are named after the crayfish that once and still live here. Like the Kroißental in St, George and Groisbachn in Sommerein (Krizsanits and Horvath 2012).

The Leitha hills is also connected with wine. For centuries it has characterized the landscape, influenced the shape of the villages and road segments. In the 18th century a lot the wine yards were turned into farmland because of increase in taxes. Indeed, in the past there were much more wine yards and fruit trees around and on the Leitha hills. Important were the cellars, mostly built against the slope of the hill and covered with earth to realise the optimal climatic circumstances. Not all the places were well suited for growing grapes. The local place names revealed often the quality. For example Goldberg for good quality and Steinweingarten for bad conditions. Fruit trees characterized the landscape as they were often built along roads.

Around the Leitha hills has during the centuries a pilgrimage culture developed and also hunting took place. Although, it was for a long a privilege of the nobility, as they were the main owners of the forest. The forest is crossed by large "Alleen". These were built to protect the forest from fire. Mainly on the borders almost each town had limestone quarry. The stones were carried with a horse cart to Vienna. This took six to eight hours. Finally, the Leitha hills have long history of defence, from the Hallstadt culture till modern military training areas. With all this historical information a relative chronology within the path network can be established by means of existing software packages and old maps. The resulting relative chronology model can give significant insights in the development of road and path networks in the past. This will be shown in the following paragraphs.

Harris Matrix Composer

The Harris Matrix composer is based on the concept of Harris. The software Harris Matrix Composer provide the possibility to create a digital Harris Matrix. A considerable advantage of the product, is the possibility to validate the created relations. In this way erroneous relations can be avoided and thus a wrong interpretation(Harris Matrix Composer 2013).

As mentioned before we have a network for the Leitha hills area that was for the main part automatically extracted from ALS data (Vletter 2014). When needed the network was completed manually. Then in ARCGIS the whole network was dissolved and then with feature line each road segment runs from node to node. The reason for doing this is that each road segment could have part of different network and in different times. In other words, road segment do not necessarily belong to one road or one route. In the Harris Matrix Composer, this creates some extra work. However, there is also the possibility to group entities when needed. This helps to visualize the relations between roads and paths. An important aspect is that the road segment keeps the same ID number as created in ArcGIS to maintain the consis-tency of the investigation.

In the following a selected area of 1,5 square kilometers of the Leitha hills has been used to test the applicability of the software. The specific area has been chosen because it contains both different kind of roads and paths and there are monuments in the area which give the possibility for more accurate dating. The earlier issue of re-used roads was not considered. The reason for this is that are no examples known of roads used in different periods, leading to wrong interpretation based on intersection. Therefore this possibility was not taken into account. The HMC works quite simple. Road segments that are situated above another are also above each other in the HMC diagram, connected with vertical arrows. Road segment from the same period are connected with horizontal arrows and located next to each other (Fig. 6).

OCHRE

The Online Cultural and Historical Research Environment (OCHRE) is a comprehensive database environment in which scholars record, integrate, analyze, publish, and preserve all forms of project data at all stages of research. It can be used for initial data acquisition and storage; for data querying and analysis; for data presentation and publication; and for long-term archiving and curation of data. It was developed by David Schloen (an archaeologist) and Sandra Schloen (a computer scientist) and is supported and made available to students and scholars around the world via the OCHRE Data Service at the University of Chicago. The main goal of OCHRE is to provide an environment for *integration* of all relevant data for a research project—spatial, temporal, bibliographic, image, textual, and so on—and to capture this variety of data in a way that preserves its natural format but

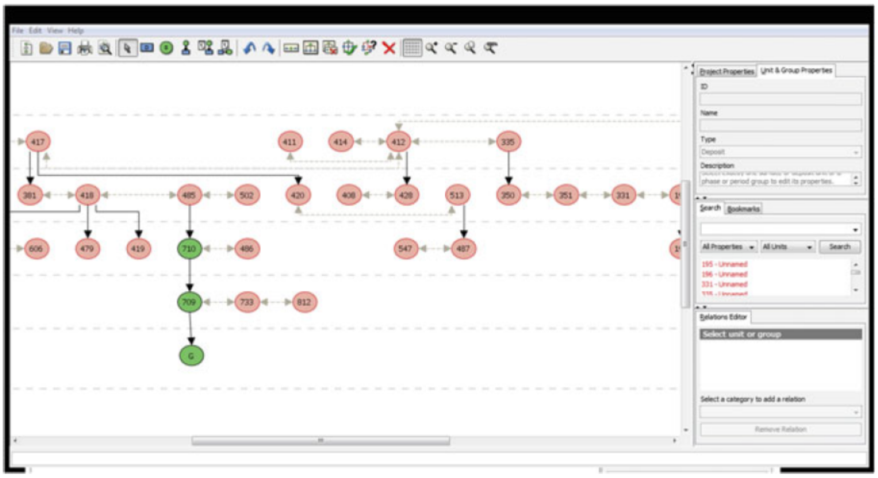
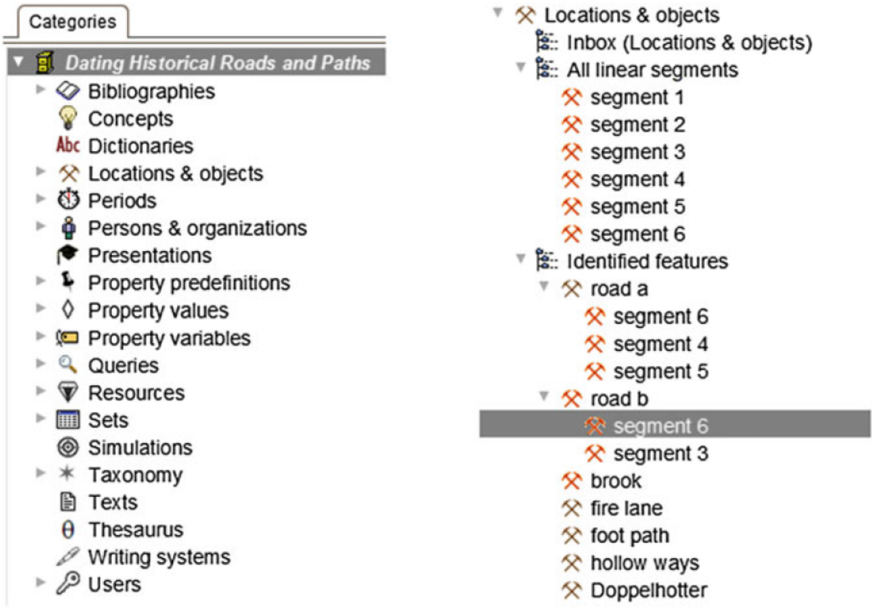


Fig. 6 Relative dating based on intersection visualised in the Harris Matrix composer. A part of the network in the study area is visible. In this part already four layers are visible. A next step in the dating process is the use of other source. This will be done within OCHRE and explained in the following paragraph

maximizes the relationships between different types of data to achieve more powerful analyses.

To accommodate a wide variety of data OCHRE uses an item-based structural model, rather than a table-based model typical of commercially available off-the-shelf software (Schloen and Schloen 2012). Any data object under consideration is uniquely identified, then described by properties, notes, links, and events. These data items are organized using hierarchical structures, a strategy which proves to be a very effective method for representing both space and time. The many categories of data managed by OCHRE are themselves structured hierarchically as shown in Fig. 7. For the scope of the *Historical Roads and Paths* project the categories **Locations & objects** and **Periods** are particularly important. Within these categories the relevant items are arranged in a tree structure.

In Fig. 7 on the right there is an example of the **Locations & objects** category in which the extracted and mapped linear features are listed within the hierarchy **All linear segments**. At this stage the linear segments are undifferentiated so they comprise, in effect, a simple list where each item is analogous to a row in a more conventional table structure. But conceptually, many of these linear segments combine to form identifiable roads and paths. One of the distinguishing features of OCHRE is that items can be arranged in more than one hierarchy, allowing the researcher to combine the items into meaningful groupings without redundancy or duplication. Here there is a second hierarchy, **Identified features**, in which identifiable roads and paths can be created from the individual linear segments in the first hierarchy, as shown in Fig. 7. In other words from segments 6, 4 and 5 one road is created (**road a**). From segments 6 and 3 **road b** is created. For this example



Categories

- Dating Historical Roads and Paths
  - Bibliographies
  - Concepts
  - Dictionaries
  - Locations & objects
  - Periods
  - Persons & organizations
  - Presentations
  - Property predefinitions
  - Property values
  - Property variables
  - Queries
  - Resources
  - Sets
  - Simulations
  - Taxonomy
  - Texts
  - Thesaurus
  - Writing systems
  - Users

- Locations & objects
  - Inbox (Locations & objects)
  - All linear segments
    - segment 1
    - segment 2
    - segment 3
    - segment 4
    - segment 5
    - segment 6
  - Identified features
    - road a
      - segment 6
      - segment 4
      - segment 5
    - road b
      - segment 6
      - segment 3
    - brook
    - fire lane
    - foot path
    - hollow ways
    - Doppelhotter

Fig. 7 On the left side, the *navigation pane* of OCHRE. On the right side, a fictitious example of the possible branching of the **Locations & objects** category

*/Locations & objects/All linear segments/segment 6
*/Locations & objects/Identified features/road a/segment 6
*/Locations & objects/Identified features/road b/segment 6

Fig. 8 Linear **segment 6** shown in each of its three organizational contexts: in the collection of all linear segments, as part of **road a**, and as part of **road b**

it becomes clear that **segment 6** is part of both **road a** and **road b**. This is of course logical when after **segment 6** the road splits up into two directions. To repeat for the sake of clarity, the creation of roads based on the individual linear segments under **All linear segments** does not mean that the segments are being copied. Instead, because of the item-based data model, the same item can exist in multiple hierarchies. In other words there no duplication of data. This is confirmed by the item's **View** which shows the item situated in three distinct contexts. Changes to *any* of these instances of the item apply directly to *all* of them because they are instances of the same database item (Fig. 8).

What applies to roads also applies to brooks. There is of course a distinction between brooks and roads or paths. A segment of a brook would also never be part of a road or path system. The case is different for the so called "fire lanes." These lanes' first objective was not as a communication way. However, from studying maps and from field walking it becomes clear that sometimes a fire lane has a double function, both as protection against fire (extension) and as a road or path. Nevertheless, this is not a problem because of the flexible, item-based model of OCHRE, in which an item (segment) can be both part of a road and part of a fire lane.

Once the segments have been organized and grouped into roads and other identifiable features, the next step is to identify the time period for those roads and features by assigning an appropriate (relative) date. Before explaining the procedure for doing this, we will first describe the **Periods** category, illustrated in **Fig.** 9.

The **Periods** category is important for the relative dating of roads, paths and fire lanes. In this category all the periods are arranged in a chronological order. Where possible a further subdivision is made. Note the use of the hierarchical structure to represent conveniently the subdivisions of the periods and the inherent relationships to the higher-level periods. If a road is dated to the **Hallstadt Culture** period, because the **Hallstadt Culture** is contained within the **Iron Age** period, the road inherits the relationship to the **Iron Age**. And so on for the other ancestors; since the **Iron Age** is contained within the **Prehistoric** period, the road will inherit the link to the **Prehistoric** period too. Because of the hierarchical inheritance, a query that searches for all roads in existence during the **Prehistoric** period will include in its matching results all roads that are assigned to the **Hallstadt Culture** period. The researcher can assign to a road the most specific period that is relevant or that can be known, but then the road inherits the relationships to all of the hierarchically related ancestor periods (Fig. 10).

Until the Roman period we can only base the evidence on archaeological finds. This is often not a very secure source. In an earlier statement, it was already

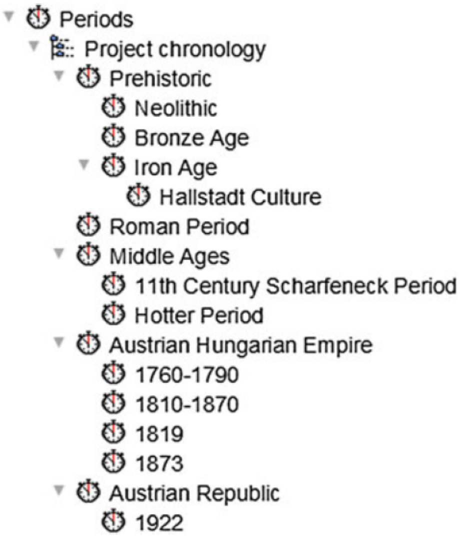
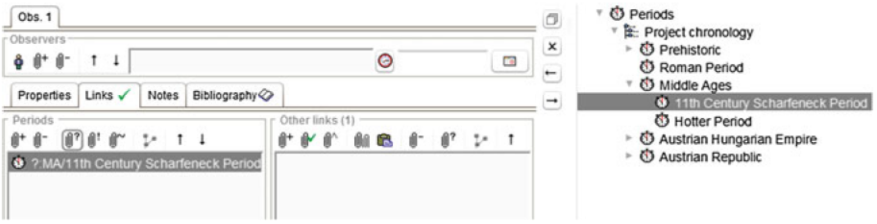


Fig. 9 The time periods distinguished for the Leitha hills

- Periods
  - Project chronology
    - Prehistoric
      - Neolithic
      - Bronze Age
      - Iron Age
        - Hallstadt Culture
    - Roman Period
    - Middle Ages
      - 11th Century Scharfeneck Period
      - Hotter Period
    - Austrian Hungarian Empire
      - 1760-1790
      - 1810-1870
      - 1819
      - 1873
    - Austrian Republic
      - 1922



?:MA/11th Century Scharfeneck Period

Fig. 10 An item is dated by assigning a link to an appropriate Period from the **Periods** Category using the **Linked Items** pane in the right-most OCHRE panel. Such links can be marked as uncertain

mentioned that a road running along a Neolithic monument does not mean that the road is also Neolithic. However, sometimes there are strong indications in the landscape that make dating to prehistoric times likely. OCHRE allows the researcher to tag a link to a period with a question mark, thereby indicating the uncertainty of the identification. From the Roman times onward, the written sources gain importance. We know for example that the Castle Scharfeneck was built in the 11th century. There is only one road running to the main entrance and no other options seem suitable, so we can quite confidently date this road to the same period. Other examples are the (Doppel) Hotter. These are border markers put on the ground in the Middle Ages. Often a road runs alongside such a border marker. This also gives a quite good indication of the date of the road, although less clear than the example of the Scharfeneck castle.

One of the strengths of the OCHRE approach is that a certain object, a group of hollow ways with a long history in this case, can be linked to different periods. If for example based on archaeological evidence, there is a strong indication that their use has mainly occurred in the Neolithic this can be assigned by clicking the paperclip link button with the exclamation mark (see Fig. 11). It is also possible that other persons have other interpretations of the predominant use. In this case a new project user can be added, who gives his or her own interpretation by adding a new *observation* to the same database item. Each observation can be tagged as to the observer and the date of the observation. In this way, scholarly discussion regarding an item of interest can be attributed and tracked.

Vletter, Willem
2014-04-30

~:*:Austrian Hungarian Empire [preliminary;predominant]
Austrian Republic

hollow ways, shapefile

Fig. 11 An observation is made detailing the attested dates of the hollow ways

From the beginning of the 19th century accurate maps also became available. Once these are georeferenced and laid over the ALS data, the relative time depth of roads and paths becomes immediately clear. As mentioned earlier, one should consider old maps with care as they are often not complete. One can imagine for example that small paths were not mapped. A good example of this is the Koningsweg from the late 17th century near Ede on the Veluwe. With the visualization technique of Openness applied to the ALS data this road is visible. However, it is not visible on the historical map from the beginning of the 19th century. On the contrary, roads of this map are not visualized with the ALS data roads.

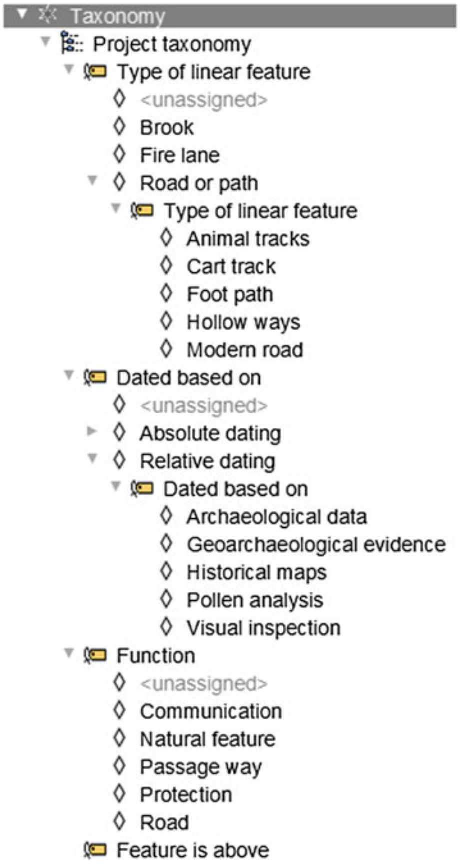
OCHRE allows all reference works and other data sources like maps to be catalogued within its **Bibliographies** category. As with the Periods above, a simple linking mechanism using OCHRE's **Linked Items** pane allows the researcher to identify the reference for the information being assigned to the item as illustrated by Fig. 12.

Along with Periods and Bibliography, OCHRE allows the researcher to set up custom properties to describe the database items. This is done in the **Taxonomy** category which, once again, is represented as a hierarchy (see Fig. 13).

The taxonomy is an alternating arrangement of **Variables** and their permitted **Values**. A **Property** is a specific instance of a variable along with the specific value that has been assigned to a given item. For example, a road item will be identified by the variable **Type of linear feature** and the value **Road or path**. What makes hierarchies so valuable again as an organizing structure is that the variable can be repeated at the next lower level of the hierarchy to further qualify the type of road or path, in this case as a **Cart track**, a **Foot path**, or a **Modern road**. As with periods, if an item is tagged with a value deeper in the hierarchy, for example a **Cart track**, it automatically inherits its ancestor values, here the **Road or path** designation. Queries for items designated as **Road or path** will, by implication, also find those items tagged as a **Cart track**.

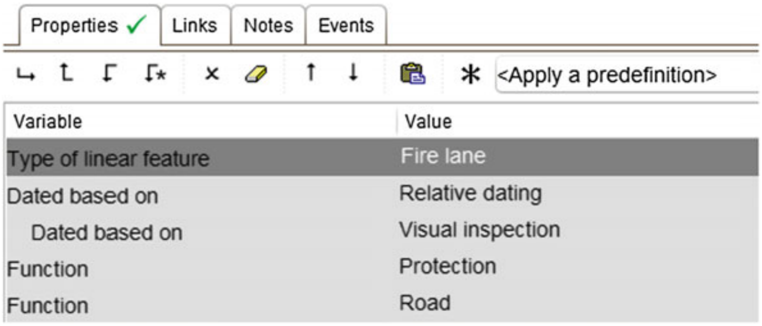
Also worth noting is that a variable can be assigned to an item more than once. To use the fire lanes discussed above as an example, they would be tagged with the **Function** variable assigned as a **Passage way**, and also as **Protection**. When a number of different properties are commonly assigned to items as a group, they can be collected together as a **Predefinition** in order to speed up the assignment of properties (see Fig. 14).

Fig. 12 A reference map is shown being linked to a fire lane item



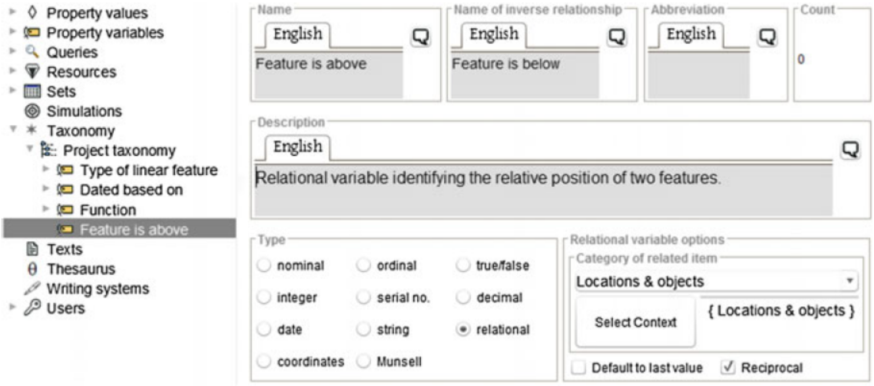
- Taxonomy
  - Project taxonomy
    - Type of linear feature
      - <unassigned>
      - Brook
      - Fire lane
      - Road or path
        - Type of linear feature
          - Animal tracks
          - Cart track
          - Foot path
          - Hollow ways
          - Modern road
    - Dated based on
      - <unassigned>
      - Absolute dating
      - Relative dating
        - Dated based on
          - Archaeological data
          - Geoarchaeological evidence
          - Historical maps
          - Pollen analysis
          - Visual inspection
    - Function
      - <unassigned>
      - Communication
      - Natural feature
      - Passage way
      - Protection
      - Road
    - Feature is above

Fig. 13 A sample user-defined taxonomy of variables and values



Variable	Value
Type of linear feature	Fire lane
Dated based on	Relative dating
Dated based on	Visual inspection
Function	Protection
Function	Road

Fig. 14 The properties of a **Fire lane** collected as a **Predefinition**. Note that the **Function** variable is intentionally assigned twice



Name: Feature is above

Name of inverse relationship: Feature is below

Abbreviation:

Count: 0

Description: Relational variable identifying the relative position of two features.

Type: ● relational

Relational variable options

Category of related item: Locations & objects

{ Locations & objects }

☐ Default to last value ☑ Reciprocal

Fig. 15 A reciprocal, relational variable used to indicate the relative position of two features

One additional type of variable of particular use here is a *relational* variable. This is a special type of variable that links one item to another as a property. As shown in Fig. 15, the **Feature is above** variable will link a source item to a related target item in the **Locations & objects** category. Typically the relation is reciprocal, and OCHRE provides an alternate label to describe the inverse of the relationship when viewed from the perspective of the target item. Here the inverse name is **Feature is below** to indicate the nature of the inverse relationship.

At the moment, relative dating based on a Harris Matrix is not yet possible in OCHRE. But it is the use of relational variables such as the one described here that will make it possible to first tag the appropriate relationships between the items, and then to use those relationships to create a Harris Matrix. Plans are underway to include new tools within OCHRE to allow auto-generation, with manual adjusting, of Harris Matrix diagrams so that all of the relative dating strategies can be integrated within a single database environment.

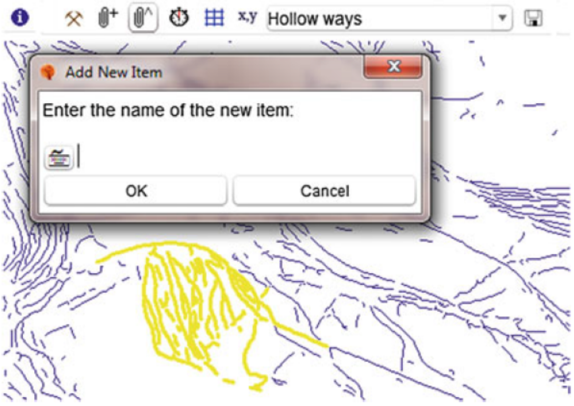
Once all the datable periods are categorized and the item properties are assigned, the identification and (relative) dating of the roads and paths can proceed. Because of the item-based data model used by OCHRE, it is typically recommended as a best-practice strategy that geospatial data be organized in such a way so that each relevant OCHRE item knows how to draw itself independently of any others. More specifically, this means that each **location** or object within the **Locations or Objects** category may have a geographic component of some kind, either a specific latitude/longitude coordinate assignment, or a point, polyline, or polygon shape associated with it. In effect, the geospatial representation of the item serves as another property of that item.

OCHRE's built-in mapping features provide an interface for displaying and working with geospatial data including *itemizing* geospatial data; that is, assigning to each OCHRE item only the relevant shape (or shapes) for that item. This provides the high degree of flexibility required by most research projects. Items can be chosen via a query using any of the properties or links assigned to them along with any of the search criteria options available in OCHRE. Because each of the items in the set of matching results can draw just itself, a map can be generated based on the query result set. Using queries that draw on all of the data associated with the roads and paths, many different aspects of the roads networks can be visualized, providing many analytical options.

Often, however, a shapefile will represent a collection of items rather than a single item. OCHRE has a special link tool in its GIS toolkit that lets a user create a new shapefile on the fly from the current selection of shapes in a map view. This newly created subset of shapes will be linked as a new shapefile to the currently selected item (Schloen 2014). Shapes can be selected by drawing a line, circle, rectangle or polygon to constrain the selection. Multiple selections can be accumulated so that all of the parts of a feature that may not lie near each other, like brooks, can be selected and assigned together. If the selection of shapes represents a new item that does not currently exist in the database, the item itself can also be created on the fly. **Properties** and/or **Periods** can be included in a **Predefinition** that is assigned to the item when the shapes are assigned, to further describe the item.

Alternately, the researcher can make a selection from the map layer's attribute table which contains a list of all the road segments. This is of course of interest with regard to the relative dating based on intersection with the HMC. The ID numbers used to identify the road segments in the HMC are the same as those shown in the attribute table. This provides a link between the separate applications which are needed until such time as the full required functionality is available within a single environment.

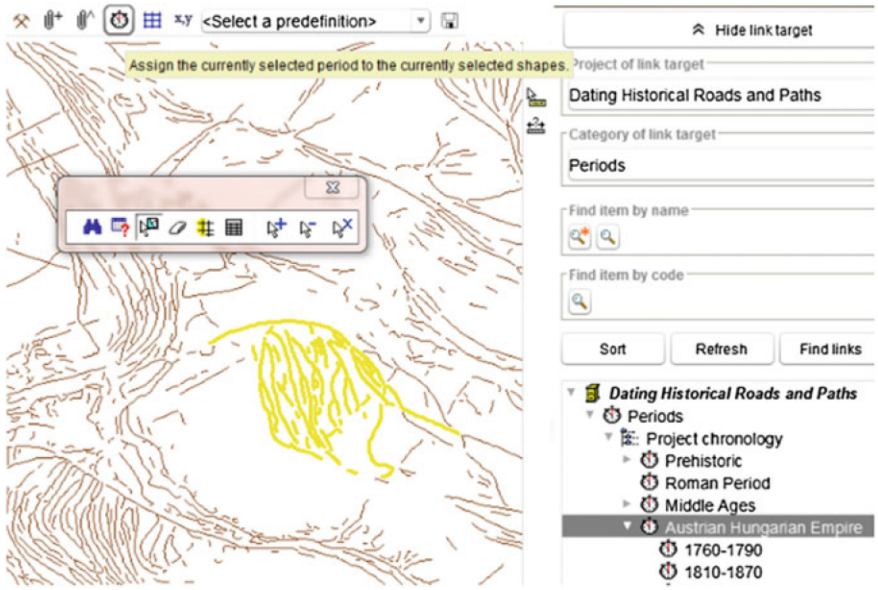
In the meantime, OCHRE's mapping interface provides tools for item tagging by **Properties** or by **Periods**. Figure 16 illustrates the creation of a new item on-the-fly to represent a group of hollow ways. The predefinition for describing hollow ways is selected to be assigned to the newly created item, the name for which is provided by the researcher. The subset of currently selected line segments becomes a new shapefile that is linked to the new item.



Hollow ways

Enter the name of the new item:

Fig. 16 A new item is created to identify a group of hollow ways; its properties are assigned by applying the **Predefinition** for **Hollow ways**. A shapefile containing the selected line segments is created and linked



Assign the currently selected period to the currently selected shapes.

Project of link target: Dating Historical Roads and Paths

Category of link target: Periods

Fig. 17 An item representing a group of hollow ways is assigned to the relevant period, in this case the Austrian Hungarian Empire

As shown in Fig. 17, dating can also be assigned to selected items in the map. The currently selected **Period** in the **Linked Items** pane (in the rightmost panel) is assigned to the currently selected item (highlighted) in the map view.

Shapefiles displayed within OCHRE, or created by the itemizing process built into OCHRE, are managed by the **Resources** category. This becomes a project's catalog of the external files that are available to OCHRE and it includes additional details about where the files are stored. These external files may include shapefiles and other image types; for this example we link in the Urmappe of 1819. A useful effect is generated by using a georeferenced map as the backdrop for the OCHRE items and their individual shapefiles. This visualization helps make sense of the relationships between features (Fig. 18).

Here it becomes more evident that the hollow ways were created after the fire lane and so must be younger. The **Feature is above** property is added to the hollow ways item's properties to capture this relationship; that is, the hollow ways **Feature is above** the fire lane. Combining the visual data, along with Bibliography, Periods, Locations & objects and Properties, captures the full details of the features within the roads and paths network (Fig. 19).

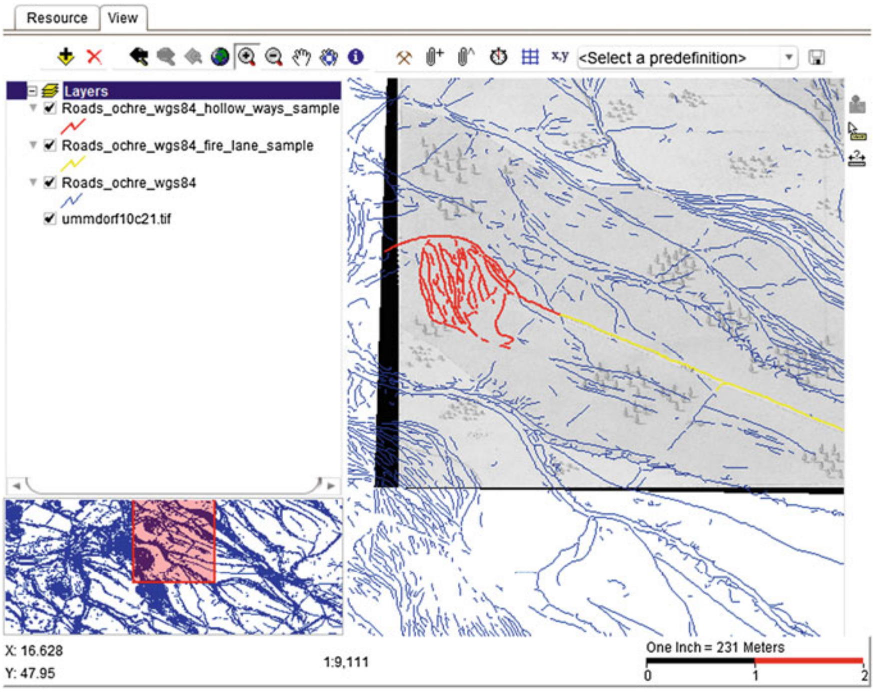
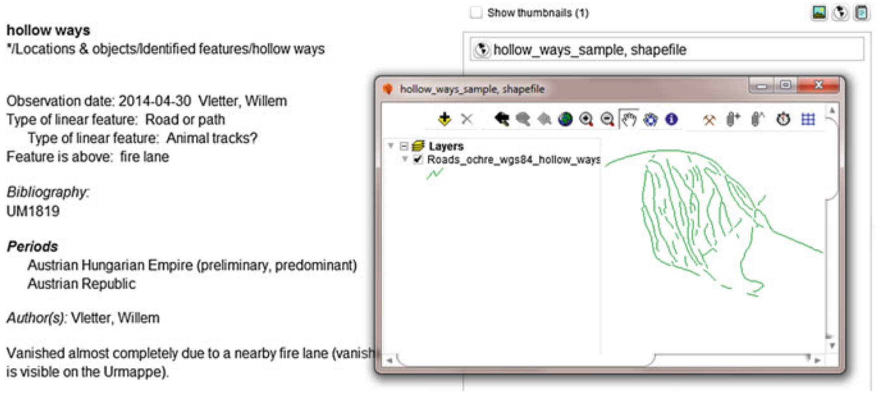


Fig. 18 The hollow ways and the fire lane overlaid together on the Urmappe from 1819



hollow ways
*/Locations & objects/Identified features/hollow ways

Observation date: 2014-04-30 Vletter, Willem
Type of linear feature: Road or path
Type of linear feature: Animal tracks?
Feature is above: fire lane

Bibliography:
UM1819

Periods
Austrian Hungarian Empire (preliminary, predominant)
Austrian Republic

Author(s): Vletter, Willem

Vanished almost completely due to a nearby fire lane (vanish
is visible on the Urmappe).

Fig. 19 The hollow ways, fully described by properties, bibliography, periods, and shape, and indicated to be above the related fire lane

Conclusion

In the end the only applicable absolute dating technique which seems worth wile for historical road research for both study areas is OSL dating in the Veluwe. Further, it can be concluded that relative dating of roads can be carried out combining different techniques and sources. An important is requisite is the availability of ALS data which can used to visualize micro relief, showing at intersections what is the relative chronology. The Harris Matrix Composer is an easy to use software package which enables to demonstrate the structural or temporal relations between roads in diagram. Important aspect of the software is that the diagram can be validated. In this way errors and thus wrong interpretation can be avoided. Extracted or mapped roads from ALS data can also be date relatively by using old maps, written sources and archaeological data. When all relative dating techniques are combined they reinforce themselves as have been shown in OCHRE. With this application a wide range of linking of items and queries are possible, which enlarge the research possibilities. One of its strengths is the tool to create subsets of the extracted or mapped network. In this way roads or brooks can be visualised separately and also be linked to certain periods. Its flexible structure allows to make distinction between road segments and to date them to different periods. The same flexibility enables multiple functions for linear features. This all contributes to a better investigation of historical roads and paths.

Acknowledgments I would like to thank Eamonn Baldwin of the University of Birmingham for his critical look at the first drafts and the staff of the OCHRE Data Service of the University of Chicago (http://ochre.uchicago.edu) for assistance and for providing complimentary student use of the OCHRE software.

References

Archaeology wordsmith. 2015. Dating and Pollen analysis. http://www.archaeologywordsmith.com/lookup.php?terms=dating, http://www.archaeologywordsmith.com/lookup.php?category=&where=headword&terms=pollen+analysis

Aston, M. 1985. *Interpreting the landscape. Landscape Archaeology in local studies*. London: B. T. Batsford

Berendsen, H. 2008. *Landschappelijk Nederland*. Assen: perspectief uitgevers.

Bourgeois, Q. 2013. *Monuments on the Horizon*. Leiden: Sidestone press.

Brindley, A.L., Lantink, J.N. 1998.Radiocarbon dates for Irish trackways. In *the Journal of Irish archaeology*, XII, 45-67.

Casparie, W. 2001. Prehistoric building disasters in Derryville Bog, Ireland: Trackways, Floodings and Erosion. In *Recent developments in wetland research.*: 115-28.

Denecke, D. 1969. *Methodische Untersuchungen zur historisch-geographischen Wegeforschung in Raum zwischen Solling und Harz*. Göttingen.

Denecke, D. 2007. Wege und Wegenetz. In *Reallexikon der Germanischen Altertumskunde* Bd.35 Berlin/New York: De Gruyter

Doneus, M., Briese, C., 2010. Airborne Laser Scanning in Forested Areas - Potential and Limitations of an Archaeological Prospection Technique. In *Remote sensing for archaeological heritage management.* Brussels: Europae Archaeologia Consilium (EAC), Association Internationale sans But Lucratif (AISBL), Siège social.

Doornebosch, M. 2014. *An environmental study of barrows.* Sidestone press. Leiden.

Ellis, C. 1998. Archaeomagnetic Dating and Palaeochannels Sediments: Data from the Mediaeval Channel Fills at Hemington, Leicestershire. In *Journal of Archaeological Science* 25: 149–63.

Harris matrix composer. 2013. http://www.harrismatrixcomposer.com/

Horsten, W.F. 2005. *Historische wegen in Nederland van 1600 tot 1850.* Amsterdam: Askant.

Hoskins, J.W. 1988. *The making of the English Landscape.* London: Guild Publishers

Johnson, M., 2008. *Ideas of landscape.* Oxford: Blackwell publishing.

Krizsanits, B., Horvath, M. 2012. *Das Leithagebirge. Grenze und Verbindung.* Weitra: Bibliothek der Provinz.

Leusen, M., van, Deeben, J., Hallewas, D., Kamermans, H., Verhagen, P., Zoetbrood, P. A. 2005 Baseline for Predictive Modelling in the Netherlands. In *Predictive modelling for archaeological heritage management: A research agenda.* (eds.) Leusen, M. van and Kamermans, H.: 28-94. Amersfoort: National Service for Archaeological Heritage.

Linford, P. 2006. *Archaeomagnetic Dating: Guidelines on Producing and Interpreting Archaeomagnetic Dates.* Portsmouth: English Heritage Publishing

McCann, W.A. 2003. The archaeomagnetic dating of two 14th-15th century hearths. In *Charter Quay, the Spirit of Change.* Salisbury: Wessex Archaeology.

McIntosh G and Catanzariti G, 2006. An introduction to archaeomagnetic dating. *Geochronometria* 25: 11-18.

Pavón-Carrasco, J., Rodríguez-González, J., Osete, M-L., Miquel Torta, J.A. 2011. Matlab tool for archaeomagnetic dating.*Journal of Archaeological Science* 38 (2):408-419.

Sanden, W. A. B. van der. 2002. Veenwegen in Drenthe: enkele nieuwe dateringe. *Nieuwe Drentse Almanak* 119: 101-112. Assen: van Gorcum

Schloen, J. D., Schloen, S.R. 2012. *OCHRE an Online Cultural and Historical Research Environment.* Winona Lake: Eisenbrauns.

Schloen, S. 2014. Itemizing shapefiles. http://ochrewiki.wikispaces.com/Itemizing+Shapefiles

Smith, N. 2011. *Pre-industrial road, track ways and canals.* English Heritage publishing.

USGS. 2015. What is Luminescence dating? http://crustal.usgs.gov/laboratories/luminescence_dating/what_is_tl.html

Vletter, W. 2014.(Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas. *SPIE proceedings Second International Conference on Remote Sensing and Geoinformation of the Environment.* doi:10.1117/12.2069709.

Vletter, W. 2015. Aworkflow for (Semi) automatic extraction of roads and paths in forested areas from Airborne Laser Scan data. *AARGnews* 50 March: 33-40

Chapter 6 The relative chronology of the road network in the Leitha Hills.

This article has been published by the peer reviewed Journal Jahrbuches „Siedlungsforschung. Archäologie – Geschichte – Geographie“ (Band 36) ARKUM in December 2019. The PhD student is the only author and thus the whole text is written by him. In this article the relative dating of roads in one of the study areas is presented.

Siedlungsforschung. Archäologie – Geschichte – Geographie 36, 2019, S. 367–384

Willem Vletter

The relative chronology of the road network in the Leitha Hills[1]

With 7 figures and 2 tables

1 Introduction

Historical roads and paths can provide much information about the use, appearance and development of past landscapes. Unfortunately, many roads and paths have vanished or been covered with layers of sediment over time. Those still present in the modern landscape and are often difficult to date. Absolute dating techniques based on the physical behaviour of the sediments are costly and not all road conditions are suitable. Relative dating can be a good alternative to establish a chronology of roads and paths, when enough datasets are available. It is based on relative age and is feasible when maps, the morphology of the roads, historical and archaeological information are available. Since absolute dates are often unobtainable, relative dating, though a poorer alternative, is often the only way to know more about the age of roads, especially on a scale of more than several square kilometers.

This case study presents the relative chronology of the road network in the Leitha Hills: it describes the area under study, the datasets and methodology used, the results obtained, and ends with a discussion and conclusion.

2 Case study area: the Leitha Hills

The Leitha Hills are a range of hills in south-eastern Austria whose name derives from the river Leitha which runs parallel on the north-western side of the area. The origin of the word Leitha is not entirely clear but is probably derived from a pre-German language and its meaning is interpreted as 'loamy stream' (*Schuster* 1990, p. 560; *Steinhauser*, 1964, p. 850).

---

[1] This contribution is based on a paper delivered at the 44th meeting of the Working Group for Research into Historical Landscapes in Central Europe (ARKUM e.V.) in Vienna on 20–23 September 2017.

Fig. 1: *The Leitha Hills (outlined in red)*
Abb. 1: *Das Leithagebirge (rot umrandet)*
Figure/Abbildung: *Willem Vletter*

The hills are about 35 km long and 5 to 7 km wide. They are considered middle mountains and connect the Alps with the Carpathians. The Sonnenberg is the highest point, its summit reaching 484 m above sea level. On the north-western side lie the Leitha river basin and on the south-eastern side the adjacent flat land runs into the marshes of Lake Balaton. The Leitha Hills are mainly forested, except for a heathland zone in the north-west. Oak, hornbeam and birch are the dominant tree species (*Krizsanits* and *Horvath,* 2012, p. 48).

The hills are barely inhabited now but in prehistoric times they were more populated, with traces of occupation attested in the Iron Age especially. Despite the limited evidence of human settlement, the hills have been exploited from prehistoric times to the present day (*Doneus* and *Briese*, 2011, p. 68–69). Activities such as forestry, stone quarrying, charcoal burning, stock breeding and religious activities can be detected from the remains they left in the landscape, from historical sources and from toponyms.

Geologically, the Leitha Hills consist of gneiss and schist with chalk on top. Gneiss was used to build walls, its resistance to fire being superior to that of chalk, and limestone was needed for its purity. The chalk, known as *Leithakalk*, was employed as building material, both as extracted blocks and as raw material burnt in chalk ovens. The *Leithakalk* was used in the northern Burgenland, which lies in the area of the Amber road; this route, known to the Romans, crossed the Leitha

Hills in the north and formed part of a pre-Roman amber trade network (*Stern,* 2008, p. 206).
The stone quarries were not, or hardly, used for centuries after the Roman period. A renewed incentive came with the foundation of monasteries and the emergence of stone-built castles in the 11th or 12th century. Indeed, old Roman stone quarries were reopened, and new quarries were established (*Hoprich* and *Tschach* 2012, p. 3).
The quarries of Au and Breitenbrunn produced *Leithakalk* in the 14th and 15th centuries to build, among other buildings, St Stephen's Cathedral in Vienna (*Bezemek* 2002, p. 14). Many buildings along the Ringstrasse in Vienna were also made of *Leithakalk* (*Bezemek* 2002, p. 323). Material from the stone quarries was used to strengthen land roads (*Bezemek* 2002, p. 380), while chalk burning is first mentioned for the year 1573 (*Starzer* 1900, p. 17).
Of course, an economic incentive as well as transport facilities were needed for the exploitation of raw materials (*Aston* 1985, p. 94). The Leitha Hills are comparable to other (middle) mountains and forests of Central Europe where a mountain industry existed in medieval times. Mining, smelting, charcoal burning, and quarrying were typical of this kind of industry (*Butlin* 1993, p. 225). Viticulture and forestry can be added to the types of exploitation present in the Leitha Hills.

Economical use

Viticulture dates back to the Iron Age and wine is still produced in the region now. The terraces and small walls are visible remains of this activity on the Leitha Hills (*Hahnenkamp* 2000, p. 42; *Doneus* 2103, p. 246). Indeed, the vineyards extended much further into the hills in medieval times (*Hahnenkamp* 2000, p. 41). Wine from Purbach was transported to Bohemia and Silesia in the Middle Ages (*Guglia* and *Schlag* 1986, p. 106) and Donnerskirchen was known in the 13th century for its vineyards (*Guglia* and *Schlag* 1986, p. 44). A copper engraving from 1695 clearly shows that the mountains behind Eisenstadt were cultivated (*Guglia* and *Schlag* 1986, p. 69), although artistic 'freedom' may have played a part in the composition of this image.

Winegrowing was at its zenith around 1600, followed by a slow but steady decline, which ended with the phylloxera catastrophe of 1893 (*Mochty* and *Bezemek* 1998, p. 296). The term *Hotter* is a dialect word for vineyard and can be found on cadastral maps (*Steinhauser* 1947, p. 108).

The pressure on the forest as a resource was high, with tensions between those who exploited the forests and local farmers. For example, local farmers wanted to use the fallen leaves and wood but gathering leaves and fallen wood depletes the humus layer and thus the productivity of the forest soil. Timber was cut in the winter and forestry put much pressure on the Leitha Hills. Indeed, much of the timber stands had already been felled in 16th and 17th century, leading to a decline in income, despite measures being introduced in the 17th century to prevent overexploitation. The demand for wood even increased in the 18th and 19th centuries, for example for brick ovens or to smoke fish (*Bezemek* 2002, pp. 181, 188, 221, 222 and 224). Berries, mushrooms, herbs and flowers were also gathered on the hills (*Bezemek* 2002, p. 225).

The grazing of cattle was also an issue. Sheep and goats were not allowed to be pastured on the hills as they ate young trees. Large domesticates like cows and horses were not subject to this limitation (*Bezemek* 2002, p. 189). The cattle were brought to the hills by a herder, who was often a child. The cattle (bullocks) brought along the trade route from Hungary and Rumania to Vienna was also pastured here, although it is not clear how this interfered with local farming practices. Finally, hay was also produced on the Leitha Hills (*Bezemek* 2002, pp. 223 and 365).

Hunting was another activity (*Bezemek* 2002, p. 351) documented on the Leitha Hills. A special deer park was built on the eastern side of St. Georgen in the 17th century and later extended in the 18th century. Hunting still takes place on the Leitha Hills but today chalk mining and forestry are the main economic activities.

Most of the villages were founded around AD 1200 (*Guglia* and *Schlag* 1986, pp. 44, 68, 106, 108; *Schweickhardt* 1830, p. 7). Some villages and castles, like Pirichendorf and Roy, disappeared at the end of the medieval period (*Hahnenkamp* 2000, pp. 17, 48 and 50), with Stotzing perhaps located on the old castle of Roy. It was founded at the end of the 16th century when the local lord, Ruprecht von Stotzingen, decided to clear a forested part of the Leitha Hills near Leithaprodersdorf to find a new village. Roman foundations or remains of the old castle of Roy were found during deforestation (*Hahnenkamp* 2000 p. 32).

To minimize cost and access time, settlements had to be located near the hills (*Aston* 1985, p. 94). Indeed, almost all villages around the Leitha Hills lie close to the forested hills, in the transition zone between the hills and the surrounding flat land. The linear *Reihendorf* (row village) settlement is characteristic of these villages, with the farms located along a stream and long strip fields behind the farms (*Born* 1977, pp. 152–156). The pilgrim villages of Loretto and St. Georgen are exceptions to this pattern. However, the land surrounding these two villages was organized in a similar way, with long, narrow strips of land. These land-use patterns are still recognizable today, especially on the eastern side of the Leitha Hills. Interestingly, the orientation of the fields can change. Close to the village they are perpendicular to a stream, especially in areas around the hills. Further away on the flat land, their orientation can shift by 90 degrees, making them perpendicular to, for example, the marshes of Lake Balaton or a road. The three-field system was in use until the second half of the 19th century on the flat land surrounding the Leitha Hills. The stabling of cattle was introduced in the same period, and dairy products became more important (*Mochty* and *Bezemek* 1998, p. 296).

Although they connect the Alps with the Carpathians, the Leitha Hills also constitute an obstacle to movement and are therefore used as an (administrative) border. Indeed, it has been a frontier zone between Austria and Hungary for a long time (*Krizsanits* and *Horvath* 2012, pp. 15–17). It is still a border between the Austrian regions of Lower Austria and Burgenland. In the forest, markers that delimited the historic borders can still be found (*Doneus* 2013, p. 246). These border markers run largely over the watershed of the Leitha Hills and are (partly) connected with a road. This suggests that a (prehistoric) ridgeway was once in existence but it is too early to draw conclusions without further research.

3 Datasets used

The datasets used for relative dating are fourfold: historical (cadastral) maps, airborne laser scan (ALS) data, extracted roads from ALS data and archaeological findings. All these sources have a geographical component, which make them suitable for relative dating in the chronological model.

The cadastral maps *(Urmappen* in German) are the main historical maps used for relative dating. Their geographical precision is greater, and they contain more detail than other historical maps. For the Leitha Hills, the boundaries of the parcels of land, the symbols for the vegetation, streams and borders, and some buildings are visible on them. However, a clear distinction in detail is noticeable among the cadastral maps. Indeed, the *Urmappen* can be divided into two groups based on their layout. On the one hand, there are coloured maps which show field names, roads, rivers and some buildings. These are mainly the older *Urmappen* from 1822 to 1856 covering mainly the former Austrian territory of that period. On the other hand, there are the (yellow) monochrome maps. These show mainly the borders between villages and some roads and date from the year 1907. Their accuracy is higher than that of the older coloured maps. This may represent a technical improvement in field survey. The monochrome maps show only streams or rivers when they coincide with borders.

In general, there is more detail and thus information visible on the Austrian maps. However, these more informative maps are not comprehensive. For example, the road to the castle of Scharfeneck is missing. This suggests that probably only the main routes were mapped and small and insignificant roads were left out.

The time difference between the oldest *Urmappe* (1819, Sommerein and Hof am Leitha) and the most recent *Urmappe* (Donnerskirchen and Breitenbrunn, 1907) is 88 years, a period long enough for a substantial change in the road network. Fortunately, most of the *Urmappen* date to the same year, 1856. This is important for connecting roads between villages on different *Urmappen*.

The so-called Perspective map of *Schweikhardt* and the military survey maps of the 18th and 19th centuries do not have the accuracy of the *Urmappe*. Nevertheless, some extra information about the roads can be gleaned from them: for example, more roads, paths and roadside crosses are shown on the Perspective map. Some roads are drawn broader, like the road between Hornstein and Eisenstadt, seemingly to show its greater importance or suitability for wheeled transport.

The ALS data come from a project led by the institute of Prehistoric and Historical Archaeology of the University of Vienna. Their characteristics are detailed below.

Table 1: Metadata of the airborne laser scan of the Leitha hills
Tab. 1: Metadaten des luftgestützten Laserscannings des Leithagebirges
Doneus and Briese 2011, p. 58

ALS project	Leitha hills
Purpose of scan	Archaeology
Time of Data Acquisition	March-12th of April 2007
Point distribution (pt. per sq.m)	7
Scanner Type	Riegle LMS-Q680i Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	36 m/s
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Robust interpolation (SCOP^{++})
DTM-Resolution	0.5 m

The presence of linear features was established and extracted from the ALS data in earlier research (*Vletter* 2014, pp. 1–11.). These features will be used as the dataset to build the model. Roads, lanes and paths constitute the main components of this dataset with additional evidence for streams, quarries and trenches.

The institute of Prehistoric and Historical Archaeology of the University of Vienna also provided the archaeological information available in ArcGIS and its interpretation of the Leitha Hills.

All these datasets were used to build the chronological model. However, it must be emphasized that this is a partial study since a complete interdisciplinary investigation would involve consulting other written sources. However, these sources lie outside the scope of the methodology employed and require knowledge of the language used in historic legislative texts in both German and Hungarian. Therefore, the methodology that has been applied to the Leitha Hills and its results can serve as input for further investigations of the historical roads and paths in the area.

4 Methodology

Building the relative chronological model requires four steps. First, the ALS data was used to classify the linear features and group them according to their physical characteristics. This represents a first interpretation, as expert knowledge is used to distinguish between features.

Second, the features were confronted with the information contained in historical maps, bearing in mind that not all the roads and paths were mapped. A division was made between features mapped on the *Urmappe* and those that were not. The Perspective map of 1830 and the three Military Survey Maps of the 18th and 19th centuries were used for this.

Third, potential links were made between historical buildings and archaeological sites on the one hand, and paths and roads on the other. Indeed, historic structures along roads can help to conserve them (*Denecke* 1969, pp. 118 and 119). However, it is risky to assign roads to a certain period if this is solely based on their proximity to a given structure. As *Hoskins* and *Taylor* write: *"If a road runs along a Bronze Age site, it does not make it a Bronze Age road"* (*Hoskins* and *Taylor* 1988, p. 191). Therefore, the linking of roads to archaeological sites must be undertaken with great caution (*Denecke* 1969, p. 37). Nevertheless, interesting links are possible.

Finally, an attempt to establish the relative age of the roads and paths from the ALS survey data was made by studying their intersections. The concept behind a chronology based on intersection is quite simple. If road A runs over road B, it means that road B is older. However, it is not always clear which road runs over the other. Hollow ways can also be quite complex as they often consist of multiple individual tracks. In this sense, an internal chronology can be established for a bundle of hollow ways (*Denecke* 1969, p. 37). Even buried wheel-tracks of a single hollow-way within a bundle can cover several centuries, as OSL (Optically Stimulated Luminescence) results have shown (*Vletter* and *Spek* in prep.). The question is whether the flat and sandy soil of the OLS-dated hollow-way examined by *Vletter* and *Spek* can be compared to the conditions prevailing in the hilly and chalky Leitha Hills. More importantly, determining an internal chronology for a bundle of hollow ways is quite complicated as tracks do not cross each other at right angles but join each other at an acute angle with no clear physical distinction based on intersections. Therefore, these internal chronologies are not considered here, and tracks in a hollow-way bundle are considered as one entity, i.e. as belonging roughly to the same period. This is of course a bias in the model. The physical depth or roads may sometimes be useful, but it depends not only on the amount of use, but also on its susceptibility to erosion. The latter depends in turn on the slope of the surface and the type of soil. The presence of natural springs, often at the beginning of a stream, causes some areas to be wetter and therefore more inclined to erosion. Therefore, caution is needed when interpretation is based on physical conditions.

The results of these four steps were eventually combined to obtain the final relative chronological model, with ArcGIS used for storing these interpretations. In particular, an attribute table which includes all the different relative dating steps was created. (see Table 2). Subsequent queries can then be made on the basis of this table to reach a final interpretation of the historical depth of roads and paths.

Table 2: Example of one the 169158 linear features in the attribute table

Tab. 2: Beispiel eines der 169158 linearen Einrichtungen in der Attributentabelle

FID	**SHAPE***	**SHAPE_ Leng**	**Periode**	**Feature**	**Feature_GR**	**Intersecti**	**Urmappe**
1687	Polyline	158.242823	PreUrm	Lane	Lanes_Donnerskirchen	Below	Yes

5 Results of the chronological model

5.1 Linear features

Grouping or classifying the linear features extracted from the Leitha Hills constitutes the first step in the chronological model. This exercise resulted in the identification of the following features:

Streams

Streams are probably the oldest linear features extracted from the ALS data. Streams, rivers and other bodies of water could have a strong influence on terrestrial movement (*Murietta-Flores* 2010, p. 255). Their main influence was in limiting the possibilities for roads and paths to follow a given trajectory, especially downstream. To avoid the effect of erosion, roads could not be too close to streams.

Roads

Many roads existed on the Leitha Hills in the past (*Bezemek* 2002, p. 167) but few historical roads are described in the literature consulted (*Starzer* 1900, pp. 62 and 63; *Schuster* 1990, p. 98; *Bezemek* 2002, p. 194; *Pollak et al.* 2006, p. 48). The roads of the monastery of St. Anna in der Wüste are probably the only roads that are datable from written sources. Since carts and wagons were used, mainly to transport wood, roads were worn into the chalk soil (*Krizsanits* and *Horvath* 2012, p. 194) to a depth that could sometimes reach several metres. These hollow ways are typically found in middle mountain zones. Most do not date further back than the late Middle Ages (*Denecke* 2007, p. 633). In medieval times, many Roman roads were abandoned and consequently lack of use and maintenance caused them to deteriorate over time. Nevertheless, many roads and paths, or segments of them survived, especially in wooded areas (*Doneus* and *Briese* 2006, p. 99). Numerous late medieval roads became deeper and increased in number in later periods (*Denecke* 2007, p. 633)

From sources dated to the 17th and 18th century, we know that local villagers were obliged to carry out maintenance. However, the roads were in such bad condition that the load they could take was limited. Interestingly, a 1715 law was designed to prevent the illegal traffic of wine and cattle across the Austrian-Hungarian border. Furthermore, it was forbidden to use roads to transport hay and wood over the Leitha Hills. A project of a law was also proposed, stipulating that the Leitha Hills could only be crossed between villages on the two sides via 'indispensable roads. Forestry roads were to be used only by owners of forests to bring their harvest back home (*Bezemek* 2002, p. 185). The need to distinguish between road use through laws indicates that roads were used for multiple purposes, not least for smuggling wine and cattle.

Fire or hunting lanes

The so-called fire lanes or hunting lanes constitute a third type of linear feature. The fire lanes were originally established to prevent a possible fire from spreading in the event of a forest fire. Hunting lanes were created for aristocratic people who wanted to have easier access to the forest and more diversity when shooting game. The main purpose of the lanes, whether fire prevention or hunting, is often not clear. It is also possible that fire lanes and hunting lanes existed next to each other or that fire lanes evolved into hunting lanes (*Konold* 2015, pp. 72–73). At any rate, rectangular patterns were cut in large parts of the Leitha Hills. Some of these lanes have evolved into (modern) roads. Their regular pattern of blocks makes them easy to recognize, given that the local geomorphology was barely considered. Not all the Leitha Hills were covered with these lanes, perhaps because property rights came into the equation. Indeed, the *Estarhazy* family and the *Scharfeneck* dynasty were large property owners, but some smaller landlords also existed (*Krizsanits* and *Horvath*, 2012, p. 193). This occasionally had consequences for the management of the forests and thus appearance

The patterns of the lanes are often limited to the edges of the villages, i.e. there is a new pattern of lanes when a border is crossed. Nevertheless, some lanes between villages are connected to each other, with sometimes sharp angles. Interestingly, not all lane intersections are at right angles to each other.

The age of the lanes is not clear. The lanes of the deer park east of St. Georgen date back to about 1750 (*Hahnenkamp* 2000, p. 57). A copper print from 1759 shows the lanes continuing outside the park further into the Leitha Hills (*Hahnenkamp* 2000, p. 59). The lanes of the deer park are visible on the First Military Survey map of 1782–1785, drawn up for the Kingdom of Hungary. Only a few lanes are visible on the Austrian maps of this first military survey, which do not appear very accurate. The row of trees along the lanes could be European beech, which is known for having been planted along such lanes (*Bezemek* 2002, p. 99). More lanes are visible on the Second Military Survey map of 1845, especially in the south-western part of the area. The number of lanes increases further on the Third Military Survey map of 1872. The number of lanes is very similar to that recorded by the ALS survey. If the maps are reliable, it means that the lanes were created in the period from 1751 to 1872.

Modern roads

Modern roads in the Leitha Hills can be split into regional roads crossing the hills and modern roads mainly used for forestry. Their width, the low earthen banks beside them and their homogeneity often make them quite easy to recognize. They play a minor role in relative dating, but the construction of these roads could have erased old tracks. Indeed, overlaying, widening and deepening these tracks will eventually obliterate the original track (see fig. 2) and hence complicate the relative dating.

Fig. 2: *The effects of tracks of modern machinery on older tracks*

Abb. 2: *Die Auswirkungen von Spuren moderner Maschinen auf älteren Wegen*

Photo/Foto: *Willem Vletter*

Until 1957, after the Second World War, Au was only reachable by a gravel road (*Bezemek* 2002, p. 379–80), indicating that modernization in and around the Leitha Hills took place very late and regional asphalted roads across the hills date mostly to the second half of the 20th century.

Quarries

Quarries, although they are not linear features, can also be identified. A clear difference in size and structure exists between old and new quarries. Indeed, the modern examples are larger, more linear and more efficiently organized, due to the use of modern machines. The morphology of the quarries seems to change over time, which could reflect technical development. Quarries at St. Anna in der Wüste were already marked on a 1689 map (*Starzer* 1900, p. 96) and it is possible that they were older than the monastery. The Perspective Maps of *Schweickhardt* show several stone quarries, and at Stotzing the presence of a quarry is noted in the accompanying text (*Schweickhardt* 1830, p. 13). These maps help date the roads leading to these quarries.

Bridges and fords

All the bridges and fords visible on the ALS survey have been mapped. Some bridges replaced fords in the past. The difference in height between banks and a stream or river, the building resources available and the importance of the road determined whether a road was replaced by a bridge. When the Turks were driven out at the end of the 17th century, new roads were built and others lost their function. However, in most cases river crossings remained in the same place. By the end of 17th century in Hungary, many wooden bridges were replaced by bridges built of stone and brick (*Winkler* 1998, p. 11). This probably also applies to the Leitha Hills area. The Rothstein bridge in the Leitha Hills was already mentioned in 1644 and bridges can be seen on the 1689 map of the monastery of St. Anna in der Wüste (*Starzer* 1900, p. 870). However, the age of bridges is generally uncertain, making them unsuitable for relative dating. Indeed, more knowledge of historic bridge architecture is needed.

Road markers

Small monuments along roads are part of the road and path networks and they usually mark single, specific points. The erection of crosses along roads goes back to the 13th and 14th century in western Europe (*Winkler* 1998, p. 21). The examples in western Hungary and probably those of the Leitha Hills date mostly from the 18th and 19th century. Penitence, commemoration, gratitude, votive purposes, protection and honour were reasons to erect crosses. Over time, crosses were increasingly placed on roads, crossings, exits of villages and the edge of forests. The crosses also served as orientation points. Statues mostly formed part of these crosses or were placed on top of columns or pillars along a road. The Trinity was often depicted, as is the case in the Leitha region. The reason for the presence of statutes was the same as that for erecting crosses. Early statues can be found as early as the 15th century in nearby Sopron but most date to much later periods. There were also votive, thanksgiving and commemorative chapels. Most were built in the Baroque period (1600 1750). Monuments and memorials often date to the second half of the 19th century and the 20th century, commemorating wars, epidemics and other events (*Winkler 1998,* pp. 9, 21, 22, 23, 35, 47, 51, 55).

Numerous, often religious, monuments were also erected in the villages around the Leitha Hills. A chapel was built in Eisenstadt around 1500 (*Guglia* and *Schlag* 1986, p. 68). The veneration of the Virgin Mary was a very important aspect of the Catholic Church in the 17th century. In 1673, Prince Paul had a chapel dedicated to the Virgin Mary built on a hill near Eisenstadt (*Guglia* and *Schlag* 1986, p. 37) A Trinity column was erected in 1713 when the plague devastated this area (*Guglia* and *Schlag* 1986, p. 70). In Au, a commemorative plague statue was erected in 1713 (*Bezemek* 2002, p. 178). Chapels were built in Mannersdorf in 1743 and 1747. Further, a pillar dedicated to the Virgin Mary was set up in the 18th century in this village. There was a stone cross at St. Anna in der Wüste which in 1689 was replaced by a statue of St. John (*Starzer* 1900, pp. 22, 44, 45, 96).

Since crosses in the Leitha Hills are not often mentioned in the literature, historical maps can help identify them and pinpoint their location. The crosses in the Leitha Hills are likely to date to the 17th and 18th century. They were probably placed along the roads that carried most traffic across the Leitha Hills at the time. Therefore, the crosses may indicate the roads that were most heavily used at a given period. However, it does not mean that they were the oldest roads.

5.2 The relative chronology

The interpretation of the chronology of paths and roads in the Leitha Hills was complicated by three main issues. First, roads which seem to date from the time of the *Urmappe* (early 19th century) were not drawn on it. Second, modernized roads caused uncertainty because, if they were built over or along old tracks, it was sometimes difficult to interpret them. If a hollow-way was adapted in modern times, it was still considered an historic hollow-way and visualized as such. Third, there were issues of accuracy for some roads on (cadastral) maps.

Four periods can be distinguished, based on the methodology described and the presence of possible prehistoric roads. Going back in time, the first map shows modern roads built after the *Urmappe*, i.e. roughly after 1856. However, most roads were built in the 20th century for forestry and as regional roads. For the sake of clarity, only these recent roads are shown on the map illustrated in figure 3, with historical roads still present in the landscape being left out.

The period of the *Urmappe* covers the next period, around 1856. These are roads and lanes visible on the *Urmappe*, which thus existed and were probably used in that period. Again, the *Urmappe* does not provide a complete picture of the roads and paths that existed. This is confirmed by comparing historical maps, which seem reliable, with the ALS data.

The next map shows the roads and paths that existed before the *Urmappe* was drawn. The intersection of roads and paths with the roads and lanes drawn on the *Urmappe* plays an important role in this map, with the hunting or fire lanes being

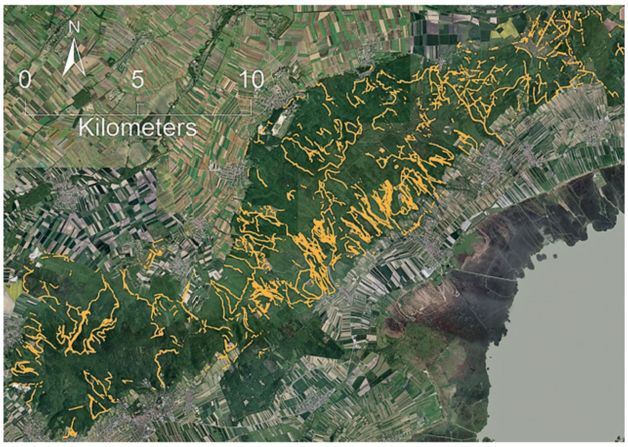


Fig. 3: Roads and paths later than the Urmappe

Abb. 3: Straßen und Wege, die später als die Urmappe sind

Figure/Abbildung: *Willem Vletter*

Fig. 4: *Roads, paths and lanes on the Urmappe*

Abb. 4: *Straßen, Wege und Pfade, die auf der Urmappe gekennzeichnet sind*

Figure/Abbildung: *Willem Vletter*

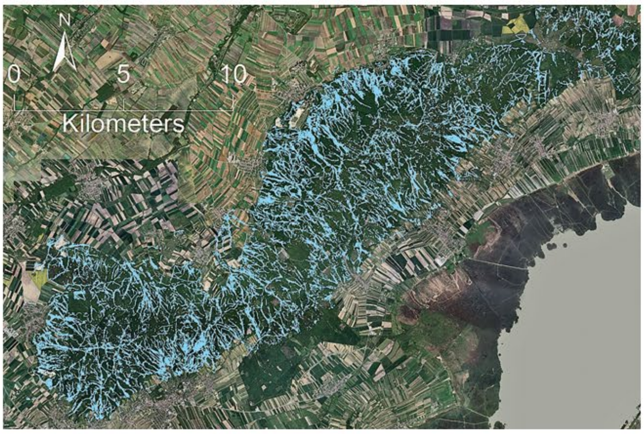


Fig. 5: *Roads and paths older than the Urmappe*

Abb. 5: *Straßen und Wege, die älter als die Urmappe sind*

Figure/Abbildung: *Willem Vletter*

Fig. 6: *Roads and lanes older than the 17th and 18th century*
Abb. 6: *Straßen und Wege, die vor dem 17. und 18. Jahrhundert vorhanden waren*
Figure/Abbildung: *Willem Vletter*

often decisive. Almost all the hollow-way bundles run under them, meaning they are older than the period of the *Urmappe*. This makes them at least earlier than 1856, but they probably existed in the 18th or perhaps 17th century. Infrastructure, like the paths to the hermitage cells of St. Anna in der Wüste, is included in this map.

The map illustrated in figure 6 shows hollow-ways which lay below the hollow-ways of the previous map. Indeed, a chronology based on intersections sometimes seems to be discernible. The layout of these hollow ways, with small depressions and less homogeneity, makes them look older. Of course, local susceptibility to erosion could blur the picture. These earlier hollow-ways can be found in several places on the Leitha Hills. However, they are not as densely spread as the later (bundle of) hollow-ways. It is difficult to assign them to a specific period but, if they are older than the later hollow-ways, they may perhaps date to the 16th or even 15th century. The road to Scharfeneck, whose castle was built in 15th century, is included in this map (*Starzer* 1900, p. 49).

The oldest roads are the roads which can possibly be linked to (prehistoric) archaeological features (fig. 7). Again, great caution is necessary when attempting dating based on archaeological features and hence only roads and paths actually leading to archaeological features should be considered. In the Leitha Hills, road and paths are almost impossible to link with any certainty to archaeological features. The entrance to the Iron Age hillfort (*Burgstelle*) in Purbach seems to be the only exception. *Michael Doneus* came to the same conclusion earlier (*Doneus* 2013, p. 324).

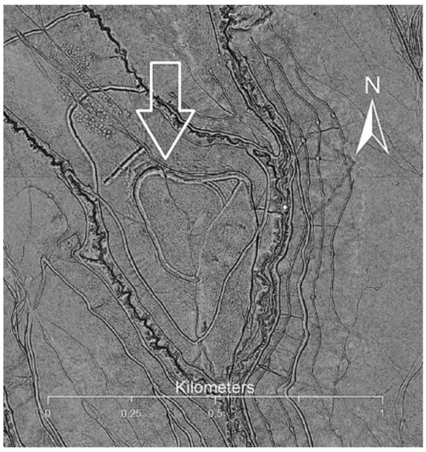


Fig. 7:
Possibly very old roads
Fig. 7:
Möglicherweise sehr alte Straßen
Figure/Abbildung: *Willem Vletter*

6 Discussion

Creating a relative chronology for the Leitha Hills is labour-intensive, the large amount and variety of features being the main cause. Tools in ArcGIS help to store the classification, the interpretation and the intersection of features but it is time-consuming. Machine learning seems a promising development and may in future reduce the amount of time required. However, it is a challenge to build an application capable of differentiating between features and create a relative chronology based on intersections. Indeed, smart machines will be necessary to understand, for example, the subtle differences between an historic hollow-way and a modern forestry road.

Knowing the history of the Leitha Hills and it surrounding villages is extremely important for culture-historical interpretation and thus the chronological model. Although this is patently obvious, it still happens that ALS data are interpreted without consulting historical sources.

The historical maps are an added value. The *Urmappen* are especially helpful to create the chronological model, although it is sometimes hard to recognize mapped roads on the ALS survey because of multiple tracks.

The chronological model presented here, consist of four period layers and a possible prehistoric road. The model seems to reflect the written sources. Indeed, due to increased forestry exploitation, an expansion of the road system (hollow ways) took place, probably from the 17th century until the 19th century. A division between early and late hollow ways seems feasible. The lane structures were added to the hollow ways from the second half of the 18th century to the late

19th century. Finally, modern machinery, mainly in the second half of the 20th century, introduced new roads for forestry and other regional exploitation.

Some roads may have been in existence from early modern times onwards (16th century) or even from the late Middle Ages (12th 15th century). To leave permanent traces, roads need to have been used over a certain duration. This combined with erosion processes, results in none or hardly any, of the road dating back to early medieval times.

Possible future research could include the study of bridges to date the roads crossing them. A further assessment of roadside crosses may also bring new insights. Although roads seem to have been used for multiple purposes, it may be possible to further distinguish between their various uses. All these topics require more fieldwork. Indeed, fieldwork is still fundamental for historical road research, despite the use of modern technology and the existence of historical datasets. This was also the case in the investigation presented here.

7 Conclusion

Relative dating is applicable to the Leitha Hills and would be appropriate for similar middle mountain areas. However, good ALS data as well as detailed and accurate historical maps are needed. For large areas like the Leitha Hills, it is quite laborious to create a chronological model. Machine learning may reduce working time in the future. The outcome of the chronological model provides greater insights into the sequence of roads on the Leitha Hills and provides a good basis for further research into the road and paths system in existence there.

Summary

A lack of reliable and economic methods often renders the absolute dating of historical roads and paths difficult and hence relative dating offers greater and cheaper possibilities. The aim of this study was to explore the relative chronology of the road network in the Leitha Hills in Austria and create an appropriate model. Airborne Laser Scan (ALS) data, historical maps and archaeological datasets were combined to create a model that comprises four or five layered periods. New insights in the development of the network were gained and the relative dating in the study area gave added value to the investigation of historical roads. The prospects for follow-up research look promising and the methodology presented here is also applicable in other areas.

Zusammenfassung

Die relative Chronologie der Grenzen und Wege im Leithagebirge

Absolute Datierung von historischen Wegen und Pfaden ist oft wegen des Mangels an verlässlichen und wirtschaftlichen Methoden schwierig. Relative Datierung bietet mehr und kostengünstige Möglichkeiten. Deswegen war das Ziel dieses Beitrags ein relativchronologisch Modell für das Wegenetz der Leitha Berge in Österreich zu untersuchen. Airborne Laser Scan (ALS) Data, historische Karten und archäologische Data wurden für die Erstellung dieses Modells kombiniert. Schließlich hatte sich ein Modell mit vier bis fünf Schichten für das Wegenetz herausgebildet. Neue Erkenntnisse bezüglich der Entwicklung des Wegenetzes konnten festgestellt werden. Zusammengefasst generierte die relative Datierung in diesem Gebiet einen zusätzlichen Wert der Untersuchung von historischen Wegen und ist für die Forschung viel versprechend. Außerdem ist diese Methode ebenfalls in anderen Gebieten anzuwenden.

References

Aston, Michael (1985): Interpreting the landscape. Landscape archaeology in local studies. – London: Batsford.

Bezemek, Ernst (2002): Marktgemeinde Au am Leithaberge. – Au am Leithaberge.

Born, Martin (1977): Geographie der ländlichen Siedlungen / Tl. 1. Die Genese der Siedlungsformen in Mitteleuropa. Stuttgart: Teubner.

Butlin, Robin Alan. (1993): Historical geography. Through the gates of space and time. – London: Edward Arnold.

Denecke, Dietrich (1969): Methodische Untersuchungen zur historisch-geographischen Wegeforschung im Raum zwischen Solling und Harz. Ein Beitrag zur Rekonstruktion der mittelalterlichen Kulturlandschaft. – Göttingen.

Denecke, Dietrich (2007): Wege und Wegenetz. – Berlin and. New York: De Gruyter (Reallexikon der Germanischen Altertumskunde, 35), pp. 626–648.

Doneus, Michael (2013): Die hinterlassene Landschaft. Prospektion und Interpretation in der Landschaftsarchäologie. – Vienna (Mitteilungen der Prähistorischen Kommission, 78).

Doneus, Michael and Briese, Christian (2006): Full-waveform airborne laser scanning as a tool for archaeological reconnaissance. – In: Campana, S. and Forte, M. [eds.] From space to place: 2nd International Conference on Remote Sensing in Archaeology. Oxford: Archaeopress (BAR International Series, 1568), pp. 99–105.

Doneus, Michael and Briese, Christian (2011): Airborne laser scanning in forested areas – potential and limitations of an archaeological prospection technique. – In: Cowley, D. [ed.]: Remote Sensing for Archaeological Heritage Management. Budapest: Archaeolingua, pp. 53–76.

Guglia, Otto von and Schlag, Gerald (1986): Das Burgenland in alten Ansichten. – Wien: ÖBV.

Hahnenkamp, Hans (2000): St. Georgen – Geschichte und Geschichten: Dorfchronik. – St. Georgen: Verein Dorfblick St. Georgen.

Hoprich Maria and Tschach, Maria [eds.] (2012): Als das Burgenland noch am Meer lag. – Eisenstadt.

Hoskins, William and *Taylor, Christopher (1988):* The making of the English landscape. – London: Hodder and Stoughton.

Konold, Werner (2015): Die Prägung mitteleuropäischer Kulturlandschaften durch jagdliche Nutzung. – In: Siedlungsforschung. Archäologie-Geschichte-Geographie 32, pp. 39–96.

Krizsanits, Brigitte and Horvath, Manfred (2002): Das Leithagebirge. Grenze und Verbindung. – Eisenstadt: Bibliothek der Provinz.

Mochty, Christina and *Bezemek, Ernst [eds.] (1998):* Die Marktgemeinde Hof am Leithaberge im Wandel der Zeit. – Hof am Leithaberge.

Murrieta-Flores, Patricia (2010): Traveling in a prehistoric landscape: Exploring the influences that shaped human movement. – In: Frischer, B.; Webb Crawford, J. and Koller, D. [eds]: Making history interactive. Oxford: Archaeopress (BAR International Series, 2079), pp. 249–267.

Pollak, Marianne; Ployer, Rene; Kastowski, Karolin u. Mehofer, Mathias (2006): Stellmacherei und Landwirtschaft. Zwei römische Materialhorte aus Mannersdorf. – Vienna: Bundesdenkmalamt.

Schuster, Elisabeth (1990): Die Etymologie der niederösterreichischen Ortsnamen 2. – Vienna.

Schweickhardt, Franz Xaver (1830): Perspectiv-Karte des Erzherzogthums Oesterreich unter der Ens. – Vienna.

Starzer, Albert (1900): Mannersdorf am Leithagebirge. – In: Blätter des Vereins für Landeskunde von Niederösterreich Ser. 34, pp. 37–83.

Steinhauser, Eduard (1947): Straßennamen niederösterreichischer Orte. – Hainburg: Winkelmann.

Steinhauser, Walter (1964): Der Name der Leitha und die Hunnenschlacht am Nedao. – In: Jahrbuch für Landeskunde von Niederösterreich 36, 2. Wien, pp. 844–869.

Stern, Josef, (2008): Wege um die Bernsteinstraße. – In: Burgenländische Heimatblätter 70. Eisenstadt: Amt der Burgenländischen Landesregierung, pp. 196–218.

Vletter, Willem F. (2014): (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas. – In: Hadjimitsis, D.G. et al [eds.]: Second International Conference on Remote Sensing and Geoinformation of the Environment. Bellingham: SPIE, pp. 1–11 https://doi.org/10.1117/12.2069709.

Vletter, Willem F. and *Spek, Theo (in prep.):* Regional mapping, interpretation and absolute dating of historical road systems on Pleistocene sandy soils. An interdisciplinary case study of the late medieval and early modern trade route of the Harderwijkerweg (Veluwe area, Central Netherlands).

Winkler, Gábor (1998): Auf historischen Wege Gedenkstätten und technische Denkmäler an ungarischen Landstraßen. – Budapest: Ministerium für Verkehrswesen.

Chapter 7 Archaeological features and absolute dating of historical road tracks in the North-western European Sand Belt. An interdisciplinary case study of a late medieval and early modern trade route at the Hoge Veluwe National Park (Central Netherlands).

This article has been written together with Univ-prof. Dr. Ir. Theo Spek. The latter is mainly responsible for the text from the introduction on till the methodology and the PhD student is mainly responsible for the rest of the article. The article has been published on 26 November 2020 in Landscape History. In this article a track of a route is absolutely dated.

Archaeological features and absolute dating of historical road tracks in the North-western European Sand Belt.

An interdisciplinary case study of a late medieval and early modern trade route at the Hoge Veluwe National Park (Central Netherlands)

Willem Vletter* & Theo Spek**
* Vienna Institute of Archaeological Science, University of Vienna, IC-ArchPro, Vienna, Austria; w.vletter@univie.ac.at; University of Groningen, Centre for Landscape Studies, Groningen, The Netherlands (corresponding author);
** University of Groningen, Centre for Landscape Studies, Groningen, The Netherlands, theo.spek@rug.nl

ABSTRACT

It is very difficult to obtain absolute historical datings of road features found at archaeological excavations. Nevertheless, various physical dating methods have been developed for this purpose, including Optical Stimulated Luminescence (OSL). After a small-scale archaeological campaign, samples from a medieval trading route in the Veluwe area (central Netherlands) on sandy soils have been dated with OSL, in order to compare these with archaeological and historical data of the same route. The absolute datings of tracks of this so-called Harderwijkerweg appeared to correspond largely with the archaeological interpretations and historical sources (datings between the thirteenth and seventeenth centuries). The soil profiles also revealed new insights into the diachronical development of the excavated tracks. It was concluded that the combination of archaeological excavation, OSL dating and historical archive research could be a reliable method for the dating and contextualisation of historical roads on Pleistocene sandy soils.

DOI: 10.1080/01433768.2016.???????

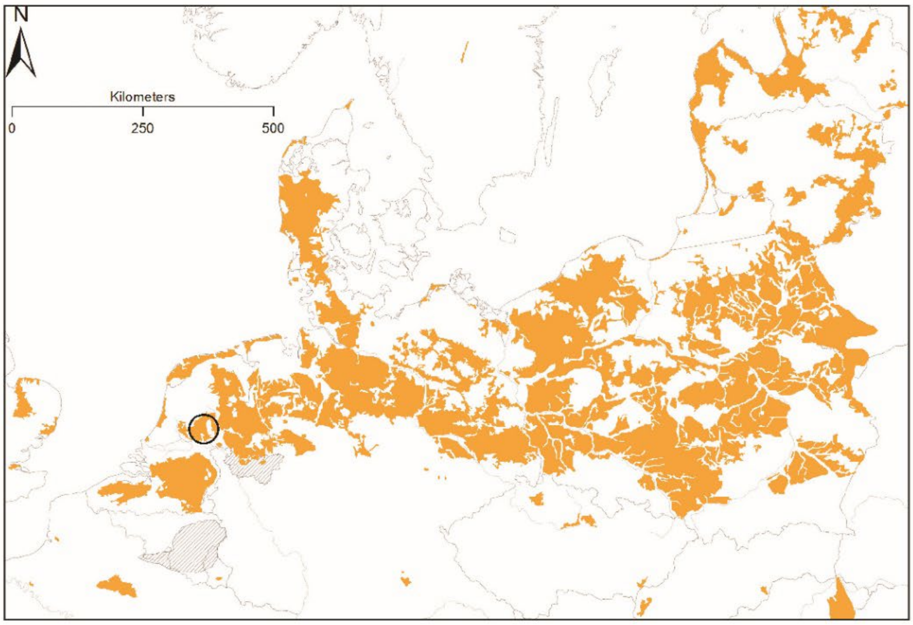
KEYWORDS

OSL dating, landscape history, historical roads, socio-economic history, airborne laser scanning

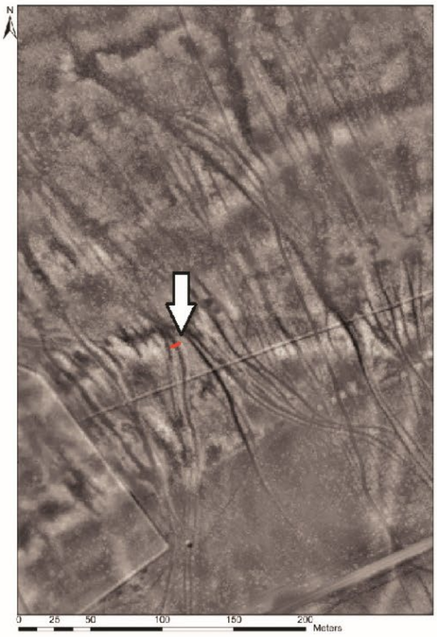
INTRODUCTION

THE LANDSCAPE SETTING

The North-western European Sand Belt stretches from northern Belgium via the Netherlands, northern Germany, western Jutland towards northern Poland (Fig. 1). It is a 50–200 km-wide belt of glacial moraines, fluvioglacial deposits and periglacial coversands, largely dating from the last three glacials and interglacials (350,000–11,700 B.P.) (Zeeberg 1998; Jones *et al.* 2005; Koster 2009). These predominantly light sandy soils have been favourable settlement areas since early prehistoric times and thus, were densely populated from the Paleolithic deep into early historic times (Behre 2008). This, however, changed in the High Middle Ages



Above: Fig. 1. Geographical distribution of The North-west European Sand Belt and location of the research area of The Veluwe within this belt.



Right: Fig. 2. Visualisation with airborne laser scanning data of historical cart tracks east of Oud-Reemst (Hoge Veluwe National Park, The Netherlands), visualization .In red, the outline of trial trench in the bundle of car tracks. Also indicated with the white arrow.

when the main settlement areas shifted towards newly reclaimed coastal plains and river valleys, and as a consequence the sandy landscapes changed towards rather loosely populated and marginal heathland farming systems (Spek 2007). Nowadays these sandy landscapes still show low population densities and have a relatively high coverage of forest plantations and heathlands.

Because of their millennia-old settlement history and low-intensive land use these landscapes show relatively good conservation conditions for anthropogenic remains, like deserted settlements, Bronze Age barrows and urnfields, prehistoric field systems and, especially, historical infrastructure. Hidden in the forests and heathlands of the

North-western European Sand Belt extensive networks of historical road systems can be detected (Van Lanen 2017; Vletter & Van Lanen 2018).

Compared to roads and routes in the adjacent peat, clay and loess areas these sandy roads show some specific characteristics. Imprints of cart and wagon tracks remain visible for many decades or even centuries after they were med, because of the rather stable sandy soil matrix and their fixation by low-growing vegetation such as semi-natural grassland, heathland vegetation or forest undergrowth. However, individual wheel tracks of a road on sandy soils show a rather quick turnover rate, as they quickly deepen and become loosened by wind and water erosion. Therefore, travellers regularly constructed a new cart or wagon track next to the old ones. Because the majority of these road systems developed in very open heathland vegetation in the past and were situated on rather stable dry soils there was hardly any limit to the lateral extension of road bundles. Over the decades and centuries this resulted into bundles of cart and wagon tracks, stretching up from several metres to sometimes 500–1,000 m in width (Fig. 2). Together these tracks tell the stories of the age-long local, regional and intraregional traffic of people and goods. Therefore, these tracks are a very challenging object for historical research as well as an important category of our common European cultural heritage.

The Hoge Veluwe National Park in the Veluwe region (Central Netherlands) contains a high number of historical road tracks from various periods. Therefore, this park was selected for our pilot project on archaeological research and OSL dating of sandy road tracks in 2015. The aim of this project was to test the combination of archaeological excavation of road features, OSL dating and contextual research of historical maps and archives for unraveling the age and history of a medieval trade route. The project is part of a more extensive Ph.D. research by the first author, aimed at the detection, dating, reconstruction and interpretation of historical road systems with Airborne Laser Scanning (ALS) (Vletter 2020).

STATE OF RESEARCH

The dating of prehistoric and historical roads is a topic that has received less attention in European research so far. As a result specific literature is scarce (Bailey 2019; Bekker-Nielsen 2004; Denecke 2007; Vletter 2015; Smith 2011; Zakrzewski *et al.* 2015). In general, two main types of dating exist in landscape history: *i.e.* absolute dating and relative dating. In absolute dating geophysical data are investigated in laboratories to provide an exact date with margins (Ellis 1998; McCann 2003; McIntosh & Catanzariti 2006; Linford 2007) Ideally, these data can be linked to historically documented events, processes or landscape features. Absolute dating projects for roads has been limited so far and often only carried out for prehistoric wooden roads (Brindley & Lantink 1998; Casparie & Stevens 2001; Van der Sanden 2002).

Relative dating provides a classification of the age between (archaeological) features, indicating which one is younger (older) than the other, without knowing an exact date. Archaeological finds, historical structures, maps and physical intersection are means to carry out relative dating (Vletter & Schloen 2015).

PROBLEM DEFINITION

For a thorough understanding of fossil roads in sandy soils it is important to take note of the fact that these roads always consist of various wheel tracks, as tracks wear out in the course of time and become too loose for efficient transport. That is the moment that a cart driver would choose to make a new and fresh track next to the old track. From the moment that a wheel track becomes deserted in favour of a new track next to it, the old track becomes more or less fossilised. Whereas the original road clearly showed a U-shape with the two separate wheel tracks of the former carts, lateral wind and water erosion gradually caused an infilling of these tracks, with a V-shaped fossilised cart track as a final result. These V-shaped tracks can be detected in the field, but also on aerial photographs or airborne laser scans. Until recently, the mapping of these fossilised tracks with the help of aerial photographs was seriously hampered by forest vegetation, which are very abundant in the sandy landscapes of the Northwestern European Sand Belt. However, with the help of modern Airborne Laser Scan (ALS) data it has become possible to make highly detailed maps of the various road systems.

Now that the detection and mapping of fossilised roads is becoming more and more feasible, the historical interpretation and contextualisation of the roads detected is one of the next problems that turns up, as well as the relative and absolute dating of individual cart tracks and road systems as a whole. How could we date exactly an individual wheel track in a road system that does not provide any organic matter suitable for radiocarbon dating? How can we reconstruct the origin and long-term development of the road system as a whole, consisting of dozens of different wheel tracks? What has been the historic trajectory and function of a particular road system? And how was this trajectory being determined by the various characteristics of the historic landscape, such as height differences, soil structure, wetness, and the location of existing settlements? These are the central questions that will be discussed in this paper.

OBJECT OF STUDY: THE VELUWE REGION AND ITS HISTORICAL ROAD SYSTEMS

The landscape

The Veluwe is a region of moraine ridges and meltwater sands in the central Netherlands of approximately 1000 km^2 (Fig. 3). Its geological backbone was formed during the Saalian Ice Age (230,000–130,000 BP) when glaciers formed a series of ice-pushed ridges 50–100 above sea level. Subsequently fluvioglacial sediments, periglacial sands and aeolian coversands filled up the glacial basins in between these moraines, resulting in an undulating region with predominantly coarse sandy soils. In prehistoric and early historic times, the elevated moraine ridges were favourite sites for settlements. As a consequence, local and intraregional sandy roads of those days were mainly situated in these elevated areas. Already in the Middle Bronze Age there must have been an extensive network of regional roads, seeing the long chains of burial mounds of this era which stretched along very straight lines (Bourgeois 2012).

Historical road systems

Between the ninth and fourteen centuries A.D. many new settlements were created in the lowlands around the Veluwe Massive, such as in the Guelders valley in the west, the Zuiderzee region in the north, the IJssele-valley in the east, and the Rhine valley in the south. Pre-medieval settlements on the higher moraine ridges founded younger daughter settlements in these valleys. The new lowland villages were mutually connected by a series of new roads on the lower outer slopes of the Veluwe. Connections between the daughter and mother settlements were created by a series of uphill and downhill roads. The lowland zones around the Veluwe were also the areas where new medieval market towns were developed by the Dukes of Guelders, such as Zutphen, Arnhem, Wageningen, Harderwijk, Elburg, and Hattem. They were mutually connected by a regional late medieval trade road system crisscross over the Veluwe Massive and passing numerous old villages, hamlets and solitary farms. One of these was the Harderwijkerweg, the medieval and early modern trade road between the flourishing late medieval market towns of Harderwijk in the north and Arnhem in the south (Fig. 4).

This settlement-oriented medieval road pattern was quite different from the new intraregional road systems of the so-called *Hessenwegen* ('Hessian roads'), roads that were developed in the Early Modern Period to permit quick long-distance merchant traffic between German towns in the east and the Golden Age towns of Holland (western Netherlands) in the late sixteenth and seventeenth century A.D. (Pieko 1993). These new trade routes had a broader wheel gauge than the previous ordinary roads, which resulted in a separate road network that avoided the existing medieval roads as well as the villages on these

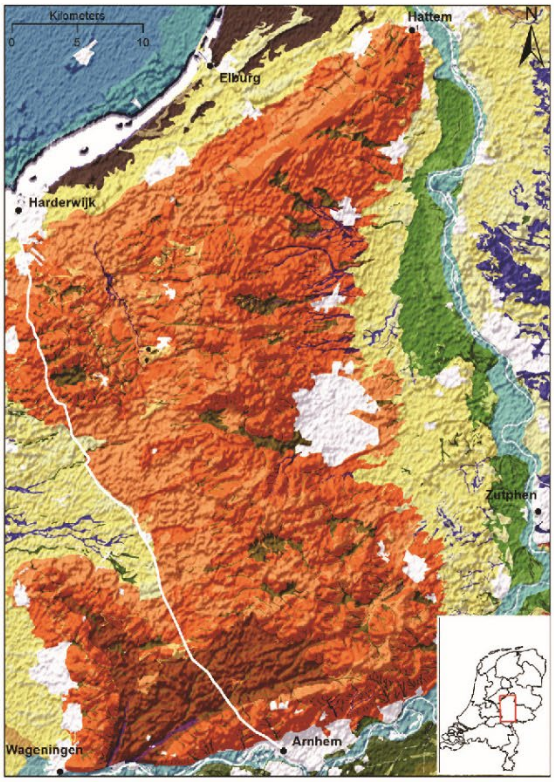


Fig. 3. Section of the archaeological landscape map of the Netherlands (1:50,000) depicting the Veluwe region and the trajectory of the medieval trade route of the Harderwijkerweg. Clearly visible are the characterising ice-pushed moraines in this area (light and dark orange sections). For a detailed description of the individual landscape units, legend and background information please see Rensink *et al.* (2017).

Fig. 4. The historical map of the Veluwe Quarter by Christiaan sGrooten from the year 1570 shows a large part of the Harderwijkerweg. Only in the northern part did the map differ from later maps.

Plate I. In the seventeenth century the trade route network of the so-called Hessenwegen (Hessian roads) was constructed. It functioned independently from the medieval village road systems and therefore mainly passed uninhabitated heathland and forest areas.

Plate II. Straight seventeenth-century hunting road of King William III at the Hoge Veluwe National Park.

roads (Pl. I). They were mainly constructed in remote heathland landscapes, which stimulated the building of several important inns.

Another interesting intraregional road network of the Veluwe was the royal hunting road network that was constructed at the Veluwe in the late seventeenth century under the authority of King William III of Holland and England. Based on his royal palace of De Loo at Apeldoorn as a starting point, he ordered to the building a series of very straight roads through forests and heathlands to his various hunting lodges on other sides of the Veluwe (Pl. II). This road system was used for the so-called 'par force hunting' by the king and his international relations (Leyden 1940; Van Heijgen 2015; Bijster & Spek 2019).

The fieldwork area

In the Dutch National Park De Hoge Veluwe a heathland area was selected which contained numerous fossil road tracks. This study area is situated on the push moraine of Oud Reemst, the soils of which mainly consist of coarse sandy and gravelly brown podzolic soils (Dutch: *holtpodzol*; soil code Y30), locally alternated with more fine coversands. The groundwater level is about 80 cm below ground level.

Until 1900, the heathlands and woodlands

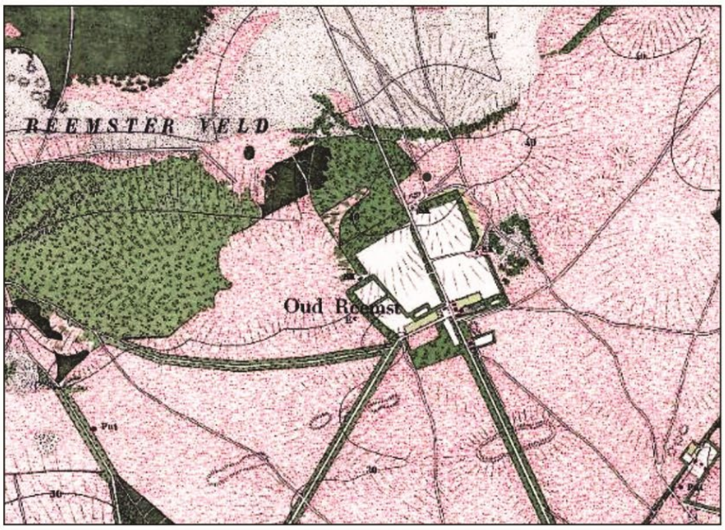


Fig. 5. Topographical map of 1900 of the hamlet of Oud-Reemst. The small farms (red) are surrounded by arable fields (white), woodlands (dark green), heathlands (pink) and sand blowings (grey).

around the small hamlet of Oud Reemst were managed as commons by local farmers (Fig. 5). The heathlands, especially, were crucial for farmers. Intensive sheep grazing and the extraction of sods for littering the stables resulted in a strong degeneration of both the vegetation and soil over the ages. Around the village, wooded embankments were constructed in order to protect the farmyards and arable fields.

The hamlet of Oud Reemst has been an intermediate station on the long-distance trading route between Arnhem and Harderwijk since the thirteenth century. As a result, the surroundings of this settlement are swarming with historical road tracks. Besides the important regional and international trade routes, a lot of local roads are visible, generated over the centuries by sheep drifts and local cart transport. Remains of them can be found in forests, sand blown areas and heathlands. Due to international changes, sheep breeding deteriorated and this pushed farmers into privatising large parts of the heathland and selling them. New farms were built on the new developed estates. Further, wooden hedges of oak coppices were laid out around the new properties. The estate owners straightened roads or built new ones. The rest of the property was parceled out in straight blocks and planted mainly with deciduous and conifer trees.

RESEARCH AIMS

This paper concentrates on the following four research aims:

1. The mapping of historical road systems of the Veluwe region with the help of Airborne Laser Scanning (ALS);
2. The reconstruction and historic contextualisation of the late medieval and early modern trade route and roads of the Harderwijkerweg historic background of this historic road systems (origin, selection of routing, function, long-term development, relics);
3. Archaeological excavation of several wheel tracks of the Harderwijkerweg;
4. Absolute dating of these excavated wheel tracks and the interrelated soil stratigraphy.

The methods that are used in these studies will be discussed in the following paragraphs.

METHODOLOGY

The historical roads have been visualised with the elaboration of Airborne Laser Scan (ALS) data. Many road tracks are distinguishable on the visualisation. However, the dating of the roads is not possible based on the basis of their outlook or intersections. Indeed, fieldwork is necessary to shed more light on their age. Therefore, a trial trench trial was dug which was planned to provide information about the physical structure, the genesis and age of a road in the Veluwe. More precisely the morphometric characteristics and stratigraphic position will be investigated, providing insight in the formation process of road traces and their post-depositional process when the road became out of use. The outcome will be compared with the OSL dating, historical sources, maps, and archaeological findings.

VISUALISATION THROUGH AIRBORNE LASER SCAN (ALS).

Airborne Laser Scan (ALS) is a technique in which from an airborne platform laser pulses are sent to the earth surface. Subsequently, a digital terrain model (DTM) is created from the returning pulses of the earth surface. Visualisation techniques can make micro-relief visible from this DTM, which is not visible with the naked eye in the field. This high-detail visibility, together with the possible large area coverage, constitutes the power of ALS for historical landscape research (Opitz & Cowley 2013; Doneus & Briese 2010; Vletter 2015).

Vegetated areas are most apposite for ALS. They contain more historical micro-relief than cultivated agricultural land (Doneus & Briese 2010; Vletter 2015). The Veluwe exists largely of forest and heathland and is therefore suitable for ALS. Indeed, many historical traces are present here. The openness technique (Yokoyama *et al.* 2002) was used to visualise the roads and paths in the Veluwe. This visualisation technique is suited for a follow up extraction step (Kokalj & Hesse 2017). The Feature Analyst tool has been used for this extraction step and has led to a high-density map with roads from different periods (Vletter & Van Lanen 2018).

DESK RESEARCH

The first part of the research will be a desk research. A contextualisation of the Harderwijkerweg is presented, based on archaeological reports, historical documents, historical maps, results of earlier research, and visualisation in geographical information system (GIS).

ARCHAEOLOGICAL EXCAVATION

An archaeological fieldwork project was prepared according to Dutch law by writing a research programme, getting permits from the official institutes and arrangement of the necessary equipment. The preparation also included the study of geophysical characteristics. The same accounted for the recognition of the historical geographical characteristics for the area. This information together with earlier findings led to an archaeological expectation of the excavation on 7 and 8 April 2014. Based on the visualisation in GIS an area was selected in order to carry out excavation. The precise location near Oud Reemst was chosen because of its clear visibility in the field. Before the excavation, the location had to be checked for explosives from the Second World War with a metal detector. One test pit, 6 metres long and 0.5 metres wide, was planned to run across a track in order to increase the probability of findimg traces. The test pit was to be excavated with a spade to expose the (subtile) layers. Further material was prepared for possible C14, botanic or OSL dating. A notebook, drawing table, a camera, and GPS measurements was foreseen as necessary to document the excavation visually and verbally in a final excavation report and in a geographic information system (GIS).

OLS DATING

Absolute dating and relative dating are the two branches of dating. With relative dating, it is determined whether a certain road is older or younger than another one. Written sources, physical intersection and historical maps can provide input to sort out the relative age. For example, building documents can help to provide information of former natural roads. Further, substantial archeological finds can give an indication for the period of use of a road or path. For natural roads, without such archaeological finds, we have to make use of other techniques to establish an absolute date or period of use. Optical Stimulated Luminescence dating is often the only technique applicable for this scope (Vletter & Schloen 2017). Therefore, this technique can be applied to the route under investigation — the Harderwijkerweg.

Optimal Luminescence dating is based on two measurements. A first measurement calculates the radiation received by a sample during its exposure to sunlight or intense heat (the zeroing event). A second measurement quantifies the accumulated luminescence signal after the last exposure to sunlight of the sample. The accumulated luminescence, caused by ionising radiation and cosmic rays, is stored as radiation. Stimulation evicts this stored radiation. Luminescence will be released and measured. The last depositional event can be calculated by combining the two measurements. Quart and potassium feldspar are normally the minerals used for OSL dating (USGS 2015).

Additional to indirect dating based on contextual information of relics in archaeological excavations or mentions in historical archives, Optical Stimulated Luminescence (OSL) is the only possible absolute dating technique so far available for roads in natural soil materials, when soil conditions are good and post-processual dynamics are low. The outcome of the OLS dating is compared with historical sources and the stratigraphic interpretation of the excavation.

RECONSTRUCTION AND HISTORICAL INTERPRETATION OF THE HARDERWIJKERWEG

ALS VISUALISATION

A detailed ALS survey of the entire Veluwe region delivered a remarkable number of road systems (Fig. 6).

Only the hollow-ways were mapped, covering a large part of the Veluwe, represented in the Geographic Information System (GIS) ArcGIS. The three main directions are discerned in the hollow-way system; crossing the push moraines from west to east, along the northern ridge and along the west side of the Veluwe area (Vletter & Van Lanen 2018). The Harderwijkerweg is part of the latter.

CONTEXTUALISATION

Traces of Iron Age and medieval settlements have been found at a distance of 1,200 metres to the north-east. Pole holes, kogelpot pottery, Merovingian pottery, Badorf pottery, Pingdorf pottery and Maasland ware made up the remains. Besides pottery, also natural stone, basalt and burned clay has been found (Van Doesburg *et al.* 2011). The settlement lies like a cape about 2 metres higher in the totally sand-blown plain of Oud-Reemst due to fact that the settlement layers and surrounding field layers were more resistant against the sand blowing.

A reconstruction of the road was made in a Least Path Cost model in an earlier research (Vletter & van Lanen 2018). Possible wetness, slope and groundwater level were the determining factors in the model, whereas height and depressions defined the possible wetness of the area. Compared to the three other investigated roads on the Veluwe, the Harderwijkerweg is most sensible to groundwater level. Indeed, it runs mostly on dry sandy soils near the transition zone to wetter peat and clay soils when seen overlaid on the soil map.

Origin

Between 1052 and 1543 the Veluwe region belonged to the political territory of the Dukes, respectively Counts, of Guelders (Noordzij 2009). At the end of the twelfth century and in the first half of the thirteenth century the dukes enfranchised a series of towns in their territory, including the towns of Harderwijk (1231) and Arnhem (1233) at the borders of the Veluwe. The latter functioned as the capital of the Veluwe Quarter in those days. Both towns showed a rapid extension and economic growth in the thirteenth century, which makes it very likely that the important trade route between both towns called the Harderwijker- or Arnhemseweg dates from the same century.

Both towns had a very strategic position. Arnhem more or less controlled the Rhine trade

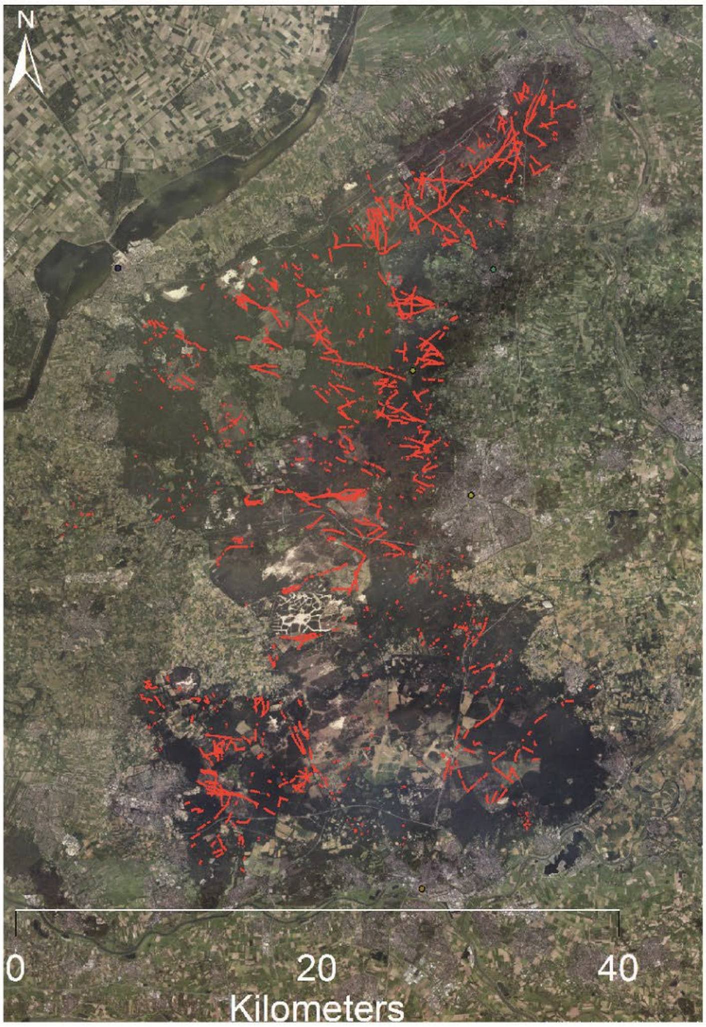


Fig. 6. Reconstruction of historic road systems of the Veluwe region by Airborne Laser Scan visualisation.

between Germany and the Netherlands and functioned as one of the main administrative and economic centres of the Dukes of Guelders in late medieval times (Verkerk 1983). In 1441, it became a member of the Hanseatic League, which connected them to many important trading centres in North-west Europe. Therefore, it is no coincidence that the Harderwijkerweg was known as the Hanzeweg (Hanseatic road) right up to the seventeenth century. Harderwijk was situated on the southern coast of the Zuiderzee, the inland sea that was directly connected to the North Sea trade and also had important textile industries and fish trade (Berends *et al.* 1968).

Historical trade route

Several sixteenth- and seventeenth-century manuscript maps depict the route of the old

Harderwijkerweg in rather high detail The very early and richly coloured map of the Veluwe of Christiaan's Grooten from the year 1570 for instance already shows a large part of the route (Fig. 4). Further, the detailed maps of Nicolaes van Geelkercken (1629; 1641), Barend Elshoff (1725) and Willem Leenen (1755) also show many details of the various parts of the route (Fig. 7). The maps make it clear that the trade route started at the north-western city gate of Arnhem leading uphill to the estate of Warnsborn and passing an extensive drift-sand and heathland landscape towards the solitary hamlet of Reemst. Close to the village of Otterlo the road passed the medieval communal forest of the Otterlose Bos and continued along the lower slope of the Guelders Valley towards Harskamp and Stroe. From there it climbed uphill again through the ancient woodlands of the Speulder, Sprielder and Putterbosch towards Ermelo, finally reaching the southern town gate of Harderwijk.

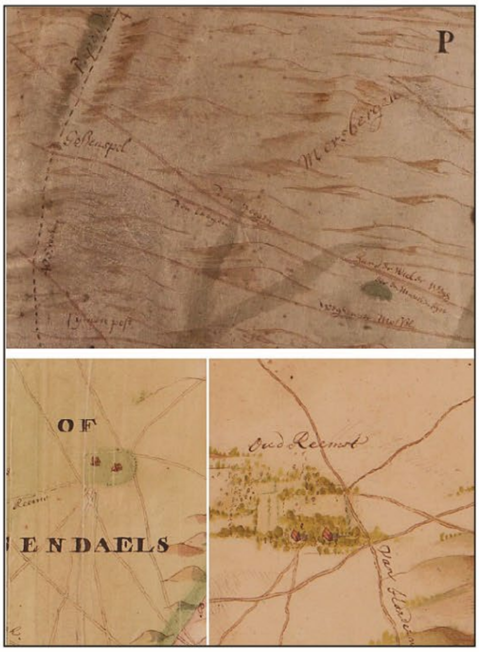


Fig. 7. Detailed maps of Willem Leenen from 1755 (central above), Barend Elshoff from 1725 (lower right) and Geelkercken van (lower left). The high and low road to Harderwijk are clearly depicted on first two the maps.

On some of the above-mentioned maps just before Oud Reemst, going in the direction of Harderwijk, Harderwijkerweg splits into a lower and upper road. Avoiding sand-blown areas in summer times, as is suggested by regional researchers, could be the reason for this (Breman & Hofman 2009). Again, this division is not always shown on maps from the seventeenth, eighteenth and nineteenth century. This may be due to the sources the maps were based on or the importance given to this division. The upper version seems to run through the forest near Otterlo; the lower one seems to be the one near or on the track of the modern Harderwijkerweg. It is not clear which one is older.

In current toponyms of roads and streets the Harderwijkerweg is still retraceable. Sometimes it is called the 'Hardwijkerkarweg', where Dutck kar stands for 'cart'. Perhaps this is an indication that mainly carts were used on the road.

Termination

Written sources and maps suggest that the thirteenth-century Harderwijkerweg functioned until the early nineteenth century. Large parts of the sandy road were then straightened and paved, and placed under the authority of the newly founded province of Guelders. Other parts became deserted and replaced by new modern roads for some distance of the old road bundle. As a large part of the Veluwe has been common heathland until the nineteenth century, and was sold to large landowners and the state in the course of the nineteenth and early twentieth century, large parts of the medieval Harderwijkerweg can still be recognised in the field.

A comparison with historical maps of Krayenhoff from 1822 and the military topographical map of 1850 show that the road in the first decade of the nineteent century was straightened and paved, causing the old cart tracks to be abandoned.

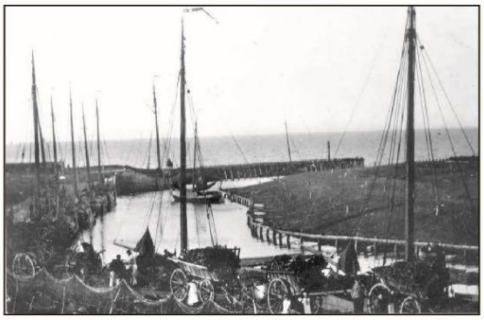


Plate III. Photo of old port of Harderwijk with carts and wagons.

Transport of goods

Fish was certainly a product transported from Harderwijker to elsewhere by carts and wagons. The Duke of Guelders gave Harderwijk the 'staple right' for fish between the Zuiderzee coastal places of Muiden and Kampen (Pl. III). This right allowed fishermen to bring fish ashore and to trade in it. The bloater (smoked and salted herring) of Harderwijk was well known for its taste. The area of the German Rhineland was provided with fish from Harderwijk. A pickling technique for anchovy, invented by a member of the Harderwijker fishermen's guild, was an improvement for the fish trade. The sold anchovy delicacy delivered high profits. However, the capture of anchovy was very irregular (Bos & Folkerts 1998). Wool, firewood, paper and rags, products from the Veluwe, were brought by cart and wagon to the port of Harderwijk for further export (*ibid*.,1998).

ARCHAEOLOGICAL EXCAVATION OF THE HARDERWIJKERWEG

The excavation trench near Oud Reemst was situated in the nature reserve on the northern side of the push moraine of Oud Reemst (Fig. 2 and Pl. IV). The area was checked for explosives with a metal detector before starting the excavation. Sunbsequently, the trench was dug across a hollow road. Archaeological finds were collected. The stratification of layers, including wheel tracks, were (preliminary) interpreted, photographed and mapped in the field. Consequently, samples were taken from wheel tracks and from just above the mother material. The wheel tracks selected had a clear uniform colour, were sufficiently large to be sampled, and looked interesting stratigraphically. Reference material was also taken from around the sample tubes. Then the samples and reference material were sent to the dating laboratory of the University of Oxford (Pl. IV). The outcome of the dating process was compared with historical sources and the interpretation of the stratigraphy. A multiple micropodzol (AE-Bhs-C), which had been developed in two thin layers of windblown sand from the late Subatlanticum, was a visible soil profile in the trench. The primary soil profile below was an of moderpodzol soil, which had been developed in coversand from the Weichselien (Bw-BCw-C).

A relatively well-preserved podzol is present on both sides of the trial trench. The layers of this soil disappeared where the wheel tracks had cut in. Instead, sand-blown layers and eluviation layers from the side originating from the time of the formation of the wheel tracks and afterwards, were deposited here.

Three layers were dug in the trench with a 10–15 cm-height difference between them. Seven wheel tracks were identified from the excavation. The odd number of seven indicates that a part of the original wheel tracks had been erased by later ones or by geological processes (erosion). Those wheel tracks situated in different layers indicate a different period.

Heavily fragmented pottery, charcoal and metal objects were found during the excavation. The pottery found existed of a Pingsdorf sherd, *kogelpot* (a Dutch term for ceramics from round cooking bowls) sherd and a piece of reddish ware pottery. The Pingsdorf and Kogelpot sherds indicate that the route was in use in the late Middle Ages (thirteenth–fifteenth centuries). The reddish ware pottery could indicate the use of the road in the fourteenth–sixteenth century. In addition, late prehistoric pottery has also been found, which could relate to late prehistoric

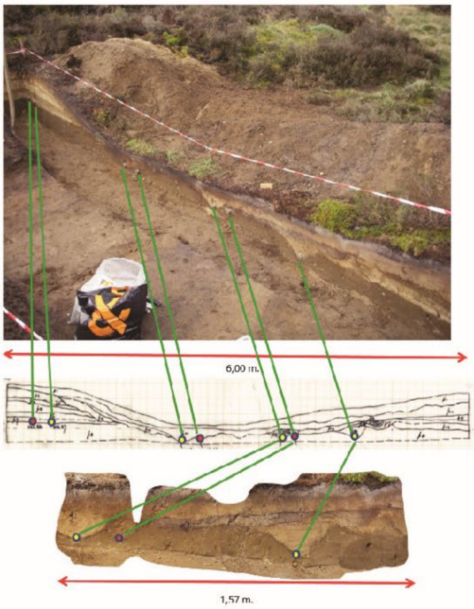


Plate IV. An overview image, the archaeological drawing and an image of a partial 3D model of the trial trench. The red and yellow dots represent the places of the OLS samples. The yellow ones, from left to right, number 26, 28, 30 and 32 in the drawing, are dated. The green lines are of orientation support for the viewer.

sites on the push moraine of Oud Reemst, such as burial mounds and Celtic fields. The small fragments of charcoal and the metal were not diagnostic.

OLS RESULTS

Plate V. A close up of the four dated OLS samples.

The OSL dating was carried out at the Research Laboratory for Archaeology and History of Art at the University of Oxford (Pl. V). The results are summarised in Table 1. The measured dates have to be calculated back from 2017, the year in which the measurement took place. Moreover, the dates have a margin indicated with ±.

The sample taken from the first windblown deposition directly next to the wheel tracks resulted in an age of A.D. 1222 ± 55 years. This matches the start of the trade route between Arnhem and Harderwijk in the middle of the thirteenth century. It corresponds with the rise of both trade cities: Arnhem got its city rights in 1227 and Harderwijk at 1231 (Verkerk 1983). OSL dates from the wheel tracks themselved showed younger datings, *i.e.* A.D. 1627 ± 30 years, A.D. 1812 ± 15 years and A.D. 1822 ± 15 years respectively. These datings reflect the long-term use of the route between the seventeenth and nineteenth centuries. Assuming that many of the old tracks have been erased due to incision by younger ones, these dates probably indicate the younger stages of use, which again corresponds with historical sources.

TABLE 1. OLS DATING RESULTS.

OSL number	Laboratory code	Age (years)	Recalculation (years A.D.)	Description
26	26 X7243	790 ± 55	1227 ± 55	Sample above mothermaterial
28	28 X7241	205 ± 15	1812 ± 15	Wheel track
30	30 X7242	195 ± 15	1822 ± 15	Wheel track
32	32 X7240	390 ± 30	1627 ± 30	Wheel track

INTERPRETATION

To find a good combination between the different wheel tracks is hard, because various types of carts and wagons, thus wheel gauges, were used in the same period (Denecke 1969; Renaud 2008). Moreover, historical sources show that the historical Veluwe had three different zones regarding the type of locally used farm wagons and carts (Renaud 2008), which means that wheel tracks could vary intraregionally. Interestingly, in a 1753 source a card type called 'Harderwijker' is mentioned and price listed for 'road money' (Pieko 1993). A typical wagon from Harderwijk seems thus to have existed. The wheel gauge, however, is not known.

Nevertheless, three possible combinations of wheel tracks can be determined in the excavation trench based on wheel gauge and the comparable volume and incision of the wheel track. A first combination has a wheel gauge of 1.29 metres, which corresponds largely with the 'Hollands Spoor' distance of 1.28 metres for a cart (Fockema 1959). The vertical surface (volume) of both wheel tracks, with a height of 10 and 8 cm and both having a maximal width of 29 cm, are similar. The depth of both wheel tracks (above sea level) shows, however, a difference of 6 cm. For a wheel gauge of 1.29 metres, this may constitute an issue. Moreover, the tracks are situated in different stratigraphic layers and this undermines the combination. Different colours, brown and light brown, of the two wheel tracks further weaken it. In another words the wheel tracks don't seem to belong together.

A second combination shows much resemblance with the one above. There is the same difference in colour — brown and light brown — between the wheel tracks, and they are situated in different stratigraphical layers. The vertical surfaces have a height from 3 to 5 cm and a maximal width from 11 to 17 cm. It assumed that neither of these wheel tracks belong together.

A third combination has the two wheel tracks in the same stratigraphic layer and colour. Moreover, they are on the same height above sea level. The wheel gauge of 0.95 metre is however quite narrow. Another issue is the difference in vertical surface (volume) between the two wheel tracks. One has a height of 16 cm and a maximal width of 35 cm and the other a height of 11 cm and a maximal width of 25 cm. The latter also makes this combination doubtful.

Sometimes it is hard to distinguish between tracks and to reveal which geological processes have taken place. Nevertheless, a westward movement of the cart track was deducted from the stratigraphy of the wheel tracks (lying on top of each other). Further, after the abandonment of the route the cart tracks have likely been partially eluviated or blown over with sand. A similar process had probably also taken place in earlier phases considering the different depths of the wheel tracks.

Two findings were located in a wheel track that has been dated to 1822. These are *kogelpot* pottery and pottery with quartz. Both late medieval finds represent a period with does not line up with the OSL. Since they have been found in the same layer no or little value can be attributed to them and they have probable been transported from other sites into the wheel track. A possible deposition is through eluviation from the adjacent push moraine. The OSL dating is therefore probably more reliable, because they line up with historical sources.

Indeed, the results of the dating correspond with the use of the route in historical times, from the period when the route came into existence in the thirteenth century to its continuous use until the nineteenth century. As such, the OSL dates neatly correspond with the historical sources. However, the dates for wheel tracks 28 and 30 are inconsistent with the stratigraphic interpretation. In this interpretation wheel track 30 lies below wheel track 28, making wheel track 30 older. The OLS dating results point to the contrary. However, wheel track 28 (1812) and 30 (1822) are very closely dated and both have an error margin of 15 years. This makes it possible that the OLS dating still coincides with the stratigraphic interpretation. Besides, a wrong stratigraphic interpretation cannot be excluded. However, a strong resemblance does also occur.

Namely, the fact that OLS 32 is older than OLS 28 and 30 coincides with the stratigraphy. Indeed, as mentioned, the stratigraphy interpretation suggests a westward movement of the wheel tracks over time. From this perspective, such *post-quem* dating of windblown layers and wheel tracks seems to offer good possibilities for the absolute dating of cart tracks.

CONCLUSIONS

The OLS datings of the Harderwijkerweg shed light on a possible use of this card track from the thirteenth until the beginning of the nineteenth century. A break between the dated periods of use is also possible. However, absolute conclusions cannot be drawn. The reason for this is twofold. Firstly, the dating, as mentioned above, should be considered cautiously. Secondly, the limited scale of the research hinders further conclusions. For instance, only one track out of a bundle of tracks was excavated and dated. It is not clear what the dating can tell about the other tracks. It is tempting to align them in the same period. However, only further excavation and dating could confirm such a hypothesis. For the Harderwijkerweg route altogether it is even more difficult to draw conclusions. Alternatives are known and the track (bundle) investigated could be one of them.

The results of OLS dating could support the view that the tracks of fossil road systems seen in the field and in the soil largely reflect the younger stages of the system, as most earlier tracks have been erased by younger wheel tracks as well as post-processual natural (erosion) and anthropogenic (agriculture and building) processes (Denecke 2007). Again, more and larger excavations and (improved) dating techniques are needed to reveal the secrets of historical roads. The Harderwijkerweg itself proved suitable for OLS dating. The outcome of the OLS corresponds largely with historical sources and with the stratification interpretation. The OSL dating and the small amount of pottery found barely correspond. Nevertheless, the OLS dating proved of value added to the historical road research. The excavation has provided insight into the structure of cart tracks and the geological and soil processes that have taken place.

Although the number of samples and dating are too low to provide a statistically reliable result, the combination of archaeology, historical sources and physical dating research (OSL) seems very promising for the near future in order to obtain more reliable absolute dates for wheel tracks on Pleistocene sandy soils in the North-western European Sand Belt. In another words OSL dating constitutes a meaningful contribution towards dating historical roads.

ACKNOWLEDGMENTS

The authors thank Dr Stijn Arnoldussen (archaeologist, University of Groningen) for his guidance of the fieldwork.

PRIMARY SOURCES

http://crustal.usgs.gov/laboratories/luminescence_dating/what_is_tl.html (no longer available)

Plate I: https://middelpuntvannederland.nl/goudsberg-schatten/goudsberg-overige-attracties-3/hessenweg-middeleeuwen/

Plate III: https://www.harderwijksezaken.nl/in-beeld/collectie-ribot-visserij-en-botters

BIBLIOGRAPHY

Bailey, S., 2019. *The Old Roads of Derbyshire Walking into History: the Portway and beyond* (Leicester).

Behre, K. E., 2008. *Landschaftsgeschichte Norddeutschlands. Umwelt und Siedlung von der Steinzeit bis zur Gegenwart* (Neumünster).

Bekker-Nielson, T., 2004. *The Roads of Ancient Cyprus* (Copenhagen).

Berends, P., Moll, J., & Van den Bosch, J.W., 1968. *Kroniek van Harderwijk 1231–1931* (Arnhem, Netherlands).

Bijster & Spek 2019. 'Snelwegen voor de koning' Onderzoek naar Veluwse wegen voor Willem III *(1650-1702) Het Nederlandse Landschap, 3, 5-15.*

Bos, C. A., & Folkerts, J. A., 1998. *De geschiedenis van Harderwijk* (Amsterdam).

Bourgeois, Q., 2012. *Monuments on the Horizon: the formation of the barrow landscape throughout the 3rd and 2nd Millennium BC (*Leiden).

Breman, G., & Hofman, P., 2009. *De Hoge Veluwe in kaart gebracht*, Hoge Veluwereeks, 6 (Valkenswaard, Netherlands).

Brindley, A. L., & Lantink, J. N., 1998. 'Radiocarbon dates for Irish trackways', *J Irish Archaeol*, 12, pp. 45–67.

Brongers, A. J., 1976. *Air photography and Celtic field research in The Netherlands*(Amersfoort, Netherlands).

Casparie, W.A. & Stevens, P. 2001 Bronze age stone-built way through an Irish bog: site Killoran 19, in *Patina: essays presented to Jay Jordan Butler on the occasion of his 80th birthday,* eds. W. H. Metz, B. L. van Beek & H. Steegstra . (Groningen/Amsterdam), pp. 195 –206

Doneus, M., & Briese, C., 2010. 'Airborne Laser Scanning in forested areas – potential and limitations of an archaeological prospection technique', in *Remote Sensing for Archaeological Heritage Management*, ed. D. Cowley (Budapest, Hungary), pp. 53–76.

Denecke, D. 1969 *Methodische Untersuchungen zur historisch-geographischen Wegeforschung im Raum zwischen Sollingen und Harz.* (Göttingen, Germany).

Denecke, D., 2007. 'Linienführung und Netzgestalt mittelalterlicher Verkehrswege – eine raumstrukturelle Perspektive', in *Straßen- und Verkehrswesen im hohen und späten Mittelalter*, ed. R. S. Schwinges (Ostfildern, Germany), pp. 49–70.

Ellis, C., 1998. 'Archaeomagnetic dating and palaeochannels sediments: data from the mediaeval channel fills at Hemington, Leicestershire', *J Archaeol Sci,* 25, pp. 149–63.

Fockema Andreae, S.J. 1957. *Hessenwegen.* Mededelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling letterkunde20/11, pp. 283–301

Jones, A., Montanarella, L., & Jones, R., 2005. *Soil Atlas of Europe* (Luxembourg).

Kokalj, Z., & Hesse, R., 2017. *Airborne Lasers Scanning Raster Data Visualization. A guide to good practice* (Ljubljana, Slovenia).

Koster, E. A., 2009. 'The European aeolian sand belt: geoconservation of drift sand landscapes', *Geoheritage,* 1, pp. 93–110.

Leyden, F., 1940. 'De jachttochten van de stadhouderkoning Willem III op de Veluwe', in *Bijdragen voor Vaderlandsche Geschiedenis en Oudheidkunde,* ed. N. Japikse, 8 (1), pp. 242–56.

Linford, P., 2007. *Archaeomagnetic Dating* (Swindon).

McCann, W. A., 2003. *The Archaeomagnetic Dating of two 14th–15th century hearths* [online], Univ Wessex Southampton. https://www.wessexarch.co.uk/sites/default/files/projects/charter_quay/Dating/archaeomagnetic.pdf [accessed 6 June 2008].

McIntosh, G., & Catanzariti, G., 2006. 'An introduction to archaeomagnetic dating', *Geochronometria,* 25, pp. 11–18.

Noordzij, A., 2009. *Gelre. Dynastie, land en identiteit in de late middeleeuwen* (Hilversum, Netherlands).

Opitz, R., & Cowley, D., 2013. *Interpreting Archaeological Topography: lasers, 3D data, observation, visualisation and applications* (Oxford).

Pieko, L. A. J., 1993. *De passagie der Hessenwegen. Over Hessen en Hessenwegen* (Oldenzaal, Neth).

Pierik, H. J., 2017. 'Past human-landscape interactions in the Netherlands. Reconstructions from sand belt to coastal-delta plain for the first millennium AD', unpubl Univ Utrecht Ph.D. thesis.

Renaud, W. F., 2008. *Wagens en karren. Diversiteit van voertuigen op het platteland en de collectie van het Nederlands Openluchtmuseum* (Zutphen, Netherlands).

Smith, N., 2011. *Pre-Industrial Road, Track ways and Canals* (Swindon).

Spek, Th., 2007. 'Kulturlandschaftsentwicklung in den Eschdörferlandschaften der nordöstlichen Niederlanden (Provinz Drenthe)', in *Historische Kulturlandschaftsforschung im Spannungsfeld von älteren Ansätzen und aktuellen Fragestellungen und Methoden. Institutioneller Hintergrund, methodische Ausgangsüberlegungen und inhaltlichen Zielsetzungen. Siedlungsforschung,* ed. W. Schenk & R. Bergmann (Bonn), 24, pp. 219–50.

Van der Sanden, W. A. B., 2002. 'Veenwegen in Drenthe: enkele nieuwe dateringen', *Nieuwe Drentse Almanak,* 119, pp. 101–12.

Van Doesburg, J., De Kort, J. W., & Schreurs, J., 2011. *Een middeleeuwse nederzetting in het Oud Reemsterzand, Waardestellend onderzoek in het Park de Hoge Veluwe in november 2009. Beknopte Rapportage Archeologische Monumentenzorg,* 22 (Amersfoort, Neth).

Van Heijgen 2015 *De Veluwe als jachtlandschap: een onderzoek* *naar de locatiekeuze en ruimtelijke inrichting van jachtgebieden op de Veluwe tussen 1650 en 1930*. Master thesis Landschapsgeschiedenis, Rijksuniversiteit Groningen, 2015.

Van Lanen, R. J., 2017. 'Changing ways. Patterns of connectivity, habitation and persistence in Northwest European lowlands during the first millennium AD', unpubl Univ Utrecht Ph.D. thesis.

Verkerk, C. L., 1983. 'Arnhem van koningsgoed tot stad', in *Arnhem. Acht Historische Opstellen*, ed. H. C. Bemmel (Gouda & Arnhem), pp. 1–40.

Vletter, W. F., & van Lanen, R. J., 2018. 'Finding vanished routes: applying a multi-modelling approach on lost route and path networks in the Veluwe region, the Netherlands', *Rural Landscapes: Soc, Environ, Hist,* 5 (1), 2, pp. 1–19.

Vletter, W., 2014. '(Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas', *SPIE proc Second Int Conference on Remote Sensing and Geoinformation of the Environment* [online], SPIE Digital library. https://doi.org/10.1117/12.2069709 [accessed 12 August 2014].

Vletter, W. 2015 A workflow for (semi) automatic extraction of roads and paths in forested areas from Airborne Laser Scan date. AARGnews50, pp 33-40.

Vletter, W., & Schloen, S., 2017. 'Creating a chronological model for historical roads and paths extracted from airborne laser scanning data', in *Digital Methods and Remotes Sensing in Archaeology. Archaeology in the age of sensing*, ed. M. Forte & S. Campana (Cham, Switzerland), pp. 405–35.

Vletter, W., 2020. 'A methodology for the use of Airborne Laser Scan (ALS) data for historical road and path research in vegetated areas', unpubl ## Ph.D. thesis. Vienna.

Yokoyama, R., Shlrasawa, M., & Pike, R., 2002. 'Visualizing topography by openness: a new application of image processing to digital elevation models', *Photogrammetric Engineering & Remote Sensing,* 68 (3), pp. 257–65.

Zakrzewski, S., Shortland, S., & Rowland, J., 2015. *Science in the Study of Ancient Egypt* (London).

Zeeberg, J. J., 1998. 'The European sand belt in eastern Europe and comparison of Late Glacial dune orientation with GCM simulation results', *Boreas,* 27, pp. 127–39.

Topic III – Reconstruction of Roads.

Chapter 8 Finding vanished roads. Applying a multi-modelling approach on lost route and path networks in the Veluwe region, the Netherlands.

The article for this chapter has been published on 5 February 2018 in the journal Rural Landscapes. The PhD student is the first author of the article. The second author, Rowin van Lanen, is responsible for texts related to the Network Friction Model. The authors wrote together the paragraphs 5 The Results, 6 Discussion and 7 Conclusion. In the article historical routes are (re-)modelled based on cultural and environmental data.

Vletter, W. F. and van Lanen, R. J. (2018). Finding Vanished Routes: Applying a Multi-modelling Approach on Lost Route and Path Networks in the Veluwe Region, the Netherlands. *Rural Landscapes: Society, Environment, History*, 5(1): 2, 1–19, DOI: https://doi.org/10.16993/rl.35

RESEARCH

Finding Vanished Routes: Applying a Multi-modelling Approach on Lost Route and Path Networks in the Veluwe Region, the Netherlands

Willem F. Vletter*,† and Rowin J. van Lanen‡,§

Route networks are influenced by cultural and environmental dynamics. Consequently, route networks themselves often are dynamic as well. This is especially true in lowland areas, such as the Netherlands, where environmental processes (e.g. geomorphological changes, floods) probably reshaped these networks numerous times. Many of the existing route networks in the Netherlands were established relatively recently, and little is known of their historical predecessors. Recent developments in spatial modelling may improve locating and analysing these old, vanished routes.

In this study we have applied two recently-developed applications for historical-route network modelling to the Veluwe (the Netherlands) in order to reconstruct the route network in the region around AD 1500. This region is not densely cultivated and is known to have a long history of routes and paths running through the landscape. The first method, network friction, uses high-resolution geoscientific and cultural data to calculate potential movement corridors and probable route zones. The second method uses a more traditional least-cost path (LCP) model based on surface, groundwater level and slope. The usefulness of these approaches for reconstructing past route networks and the general added value of these approaches was assessed by comparing the reconstructions to the few existing spatial overviews of historical-route networks in this region and hollow ways extracted from Airborne Laser Scanning (ALS) data.

Our findings show that the results of the first method, network-friction modelling, correspond best with the comparison data regarding known routes in the study area. However, the general results point towards the necessity of integrating the two applied methods, since a combination of these models best reflects the multiscale variability within regional route networks.

Keywords: Spatial modeling; routes; history; roads; paths; Airborne Laser Scan

1. Introduction

Route networks both reflect and influence (large-scale) cultural and landscape processes and therefore are key to understanding human-landscape interactions. Van Lanen et al. (2015a, 2015b) developed a new method for reconstructing large-scale (supraregional) route networks in the past. In this paper we investigate the applicability of this method and a more traditional least-cost path approach in order to improve our understanding of the layout of partly-vanished historical route networks on a regional scale. Locating vanished and abandoned routes is important because: (1) information about past routes derived from ALS data and historical sources probably only covers a small percentage of the once-existing networks and (2) route-network development can help to study human-landscape interactions in the past. Over time many routes will have disappeared mainly through dynamic geomorphological (e.g. erosion) and human-induced processes (e.g. agricultural and building activities). However, these same dynamics through route-network modelling enable us to calculate the probable location of many of these vanished routes, since not every region is equally suitable for travel and transport and therefore for hosting (persistent) route networks (Van Lanen et al., 2015a, 2016; Van Lanen, 2016).

Our study area is the Veluwe region in the Netherlands. The Veluwe is an area located in the central part of the Netherlands (ca. 1100 km^2; **Figure 1**). We selected this region as research area since high-resolution environmental (e.g. geomorphology, palaeogeography), cultural (e.g. settlement patterns) and Airborne Laser

---

* Vienna Institute of Archaeological Science, University of Vienna, A-1190 Vienna, Franz-Klein Gasse 1, AT

† Groningen University, Department of Landscape History, Oude Boteringestraat 34, Groningen, NL

‡ Utrecht University, Department of Physical Geography, Heidelberglaan 5, Utrecht, NL

§ Cultural Heritage Agency of the Netherlands, Landscape Department, Smallepad 5, Amersfoort, NL

Corresponding author: Willem F. Vletter (willem.vletter@univie.ac.at)

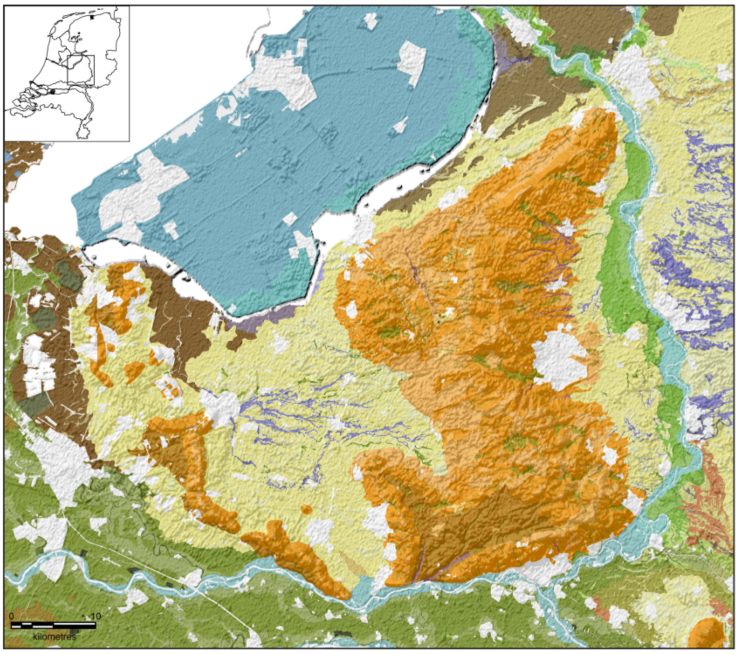


Figure 1: Section of the archaeological landscape map of the Netherlands (1:50,000) depicting the Veluwe region. Clearly visible are the characterizing high push moraines in this area (light and dark orange sections). For a detailed description of the individual landscape units, legend and background information please see Rensink et al. (2017).

Scanning (ALS) data are available, making this region well suited for a more detailed, integrated modelling approach (**Figure 2**). The region features many different landscapes including large sand drifts, woodlands and heaths. The most striking characteristic of the Veluwe is the presence of relatively high ice-pushed moraines formed during the Saalian (ca. 150,000 years ago). Additionally the Veluwe contains some very long cover-sand ridges and snowmelt water valleys. Relief in the region nowhere exceeds 110 meters (the highest point of the push moraines) and slopes are generally gradual.

It has been suggested that some of the routes on the Veluwe date back as far as the Bronze Age (2000–800 BC) and possibly are marked by prehistoric barrows (Bakker, 1976). Using visibility analyses and geographical information systems (GIS), Bourgeois (2013) underlines that these mounds might have been used as landmarks for routes, but also notes that convincing physical evidence for these routes is lacking. The earliest confirmed remnants of routes within the research area date to the late Middle Ages.

Route-network modelling is essentially a type of spatial modelling. Recently Van Lanen et al. (2015a) developed a network-friction model (NFM) in order to reconstruct Roman and early-medieval route networks. Following the definition by Van Lanen et al., "network friction is the variable that determines potential regional accessibility based on the comparison of local and surrounding landscape factors" (2015a, 200–201). This model was specifically designed to model landscape prerequisites for Roman and early-medieval route zones in dynamic lowlands where relief is often not a decisive factor for route or path orientation. By integrating cultural (e.g. settlements, burial sites) and environmental (e.g. palaeogeography, geomorphology) factors in the NFM, Van Lanen et al. (2015b) modelled possible route zones on a supraregional level for the present-day Netherlands (Appendix A). The models' outcome was validated against archaeological data on infrastructure and isolated finds and obtained good results. However, the calculated NFM-route zones were modelled using a relatively straightforward efficient path computation, i.e. the shortest distance between two settlements following the most accessible areas (Van Lanen et al., 2015b). As was already stated by Van Lanen et al. (2015a, p. 214, 2015b, p. 156), the next necessary steps for the network-friction method are to: 1) test its applicability on a more detailed regional level and for a different historical period and 2) to compare the models' outcome with results from other route-network reconstruction methods, such as the extraction of roads and paths from ALS data, and the study of historically attested routes.

In this paper we apply two different types of route-network modelling: the network-friction method and the more traditional LCP calculations. The aims of this paper are: 1) to reconstruct route networks around AD 1500 by

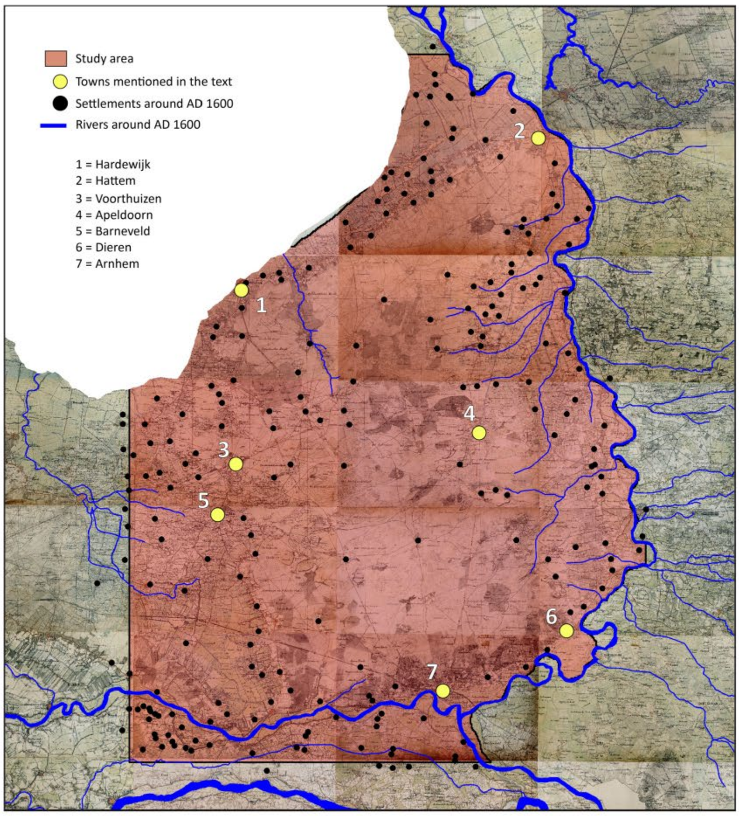


Figure 2: The research area (in red) including settlements overlaid on the Topographic Military Map 1850 (TMK 1850). Contemporary rivers are visible in blue.

applying both modelling techniques on the research area; 2) to determine the general applicability and usefulness of both approaches for route-network reconstructions on a regional scale level by comparing each outcome with data on known historical routes in the study area.

2. Route networks and GIS modelling

Over the last few decades a substantial number of papers and books have been written about spatial and predictive modelling in archaeology. Many of these primarily are theoretical exercises of exploring (technological) possibilities (e.g. Van Leusen et al., 2005; Jiang and Eastman, 2000; Murietta-Flores, 2010). Moreover, many of these studies generally have produced few results or have had relatively limited impact (e.g. Gietl et al., 2008; Verhagen, 2013; Polla and Verhagen, 2014). One of the approaches we are going to apply, LCP, can be defined as a predictive model. We define the latter as a method predicting routes or paths between two specific locations. The NFM is much more a spatial model. Although the NFM calculates potential movement corridors for probable routes based on multiple geoscientific variables, in itself it does not predict routes or paths. The NFM however does allow for the integration of large-scale archaeological data and the calculation of supraregional route zones (Van Lanen et al., 2015b). Assuming that all spatial and predictive models are "expressions of a probabilistic relationship between human behaviour and prior existing spatial conditions" (Whitley, 2005, 124), the outcomes of the NFM and LCP models can be compared.

Traditionally, LCP calculations are most common in route-network modelling. By calculating so-called friction surfaces this method calculates the most probable routes by determining which path requires the least effort to move between two points. In most cases, these friction surfaces are mainly based on the slope of the terrain. However, slope generally has not been the single decisive factor in past movement through the landscape (Howey, 2011). Alternatively, optimal-path calculations are used to better understand the formative principles of routes and paths and to compare these to historically documented routes (Posluschny and Herzog, 2011; Doneus, 2013). Other less-frequently applied route-network modelling techniques include circuit modelling (Howey, 2011) and *From Everywhere To Everywhere* (*FETE*) (White and Barber, 2012). Often these route-network modelling techniques neglect the influence of non-environmental factors (e.g. political, socio-economical, religious) which probably greatly influenced past route-network development (Bell and Lock, 2000; Llobera, 2000; Van Lanen et al., 2015b). Other studies point at the relative importance of other cost factors such as river crossings and different types of transport (e.g. by foot or carriage) in the formation of these past routes (Herzog, 2013). Van Lanen et al. (2015a, 2015b) suggest that in dynamic lowlands relief probably was not a decisive factor for route orientation, and that combined local and surrounding landscape conditions (e.g. soil types, groundwater levels) were much more decisive. Current models often are not adapted to include all these different decision-making factors (Citter, 2012). For this reason a variety of different and complementary models is needed to reconstruct historical reality (Verhagen and Whitley, 2012; Citter, 2012; Herzog, 2013; Fovet and Zakšek, 2014).

Despite the difficulty of incorporating cultural and environmental variables, predictive and spatial modelling in GIS are very promising techniques for the discovery and analysis of prehistoric and historic route and path networks. This is especially true for map-based reconstructions, because the chronology and status of known routes may be uncertain and many major connections have not yet been identified. Routes have history, and their course results from a long and complex evolution combining abandonments, changes in status and reactivations. Optimal path modelling simulating the connections between contemporary archaeological sites helps to comprehend the chronology and hierarchy of former communication networks (Fovet and Zakšek, 2014).

Past routes in our research area almost always were unpaved, implying that tracks may have wandered within route zones following broad movement corridors often several hundred metres wide. We define movement corridors as those areas where landscape setting provides people with favourable connectivity options, e.g. route zones, to other places of interests, such as settlements, fortresses, mining areas (cf. Van Lanen and Pierik, 2017; Van Lanen, 2017). These route zones filled with (seasonally) shifting tracks reflect generalized routes and should not be regarded as exact constants (Bell and Lock, 2000; Van Lanen et al., 2015b). As such, these route zones are spatially more dynamic than roads (which are much more fixed features connecting two places), but in orientation they are very similar (Van Lanen et al., 2016). Because of this flexibility, cultural and environmental factors play a decisive role in the formation of route zones. Therefore in order to accurately model these complex networks, spatial models integrating both cultural and environmental dynamics should be produced for specific cultural periods (Wilcox, 2009; Van Leusen et al., 2005).

3. Material

NFM modelling in the current study was based on the datasets used by Van Lanen et al. (2015a, 2015b; Sections 3.1–3.4). LCP modelling was based on Airborne Laser Scan (ALS) data and groundwater level reconstructions extracted from the soil maps (Sections 3.5–3.6).

3.1. Palaeogeography AD 1500

Palaeogeographical reconstructions for multiple periods were first issued in 2011 with the presentation of the Atlas of the Holocene Netherlands (Vos et al., 2011). These maps were updated in 2013 when a second generation became available (Vos and De Vries, 2013; Vos, 2015). The palaeographical reconstructions by Vos et al. (2011, 2013) and Vos (2015) describe the genesis of the Dutch landscape over the last 11,000 years. The reconstructions are multi-disciplinary in origin, combining numerous datasets from the Humanities and Geosciences, e.g. archaeology, geology, palaeoecology, onomastics and soil sciences. Therefore these maps can be used as a nationwide reconstruction of the palaeolandscape for both Holocene and Pleistocene areas.

3.2. Geomorphology

A nationwide, digital geomorphological map became available in 2003 (Koomen and Exaltus, 2003; Koomen and Maas, 2004). The map was created by combining field observations, bore hole data and surveys with detailed elevation models (Koomen and Maas, 2004). The dataset not only contains information on the individual geomorphological units, but also on relief, genesis and ages of the landscape elements on a 1:50,000 scale. Therefore the map greatly adds to our understanding of the past landscape, especially regarding the higher, more stable Pleistocene regions. As a result, the geomorphological map of the Netherlands has proven itself invaluable for archaeological predictive modelling and was used amongst others for the indicative map of archaeological values (IKAW) (Van Leusen et al., 2005; Deeben, 2008).

3.3. Soil and groundwater level data

The soil map of the Netherlands has been developed based on the soil-classification system of De Bakker and Schelling (1989). It provides an overview of all current soil types (up to a depth of 1.20 metres) in the Netherlands (Steur and Heijink, 1991; De Vries et al., 2003). Additionally, the datasets also contain data on the average groundwater levels between 1958 and 1999 (De Vries et al., 2003; Van de Gaast et al., 2010). In contrast to the geomorphological dataset, the soil map does not provide any chronological information about the ages of individual soils. Since soils change through time, the use of the soil map for historical periods requires expert judgement. This map is especially useful for the analyses of higher, more stable regions in the Netherlands, such as the Veluwe.

3.4. Settlement data

Settlement data for the Veluwe region were collected by using *OpenStreetMap* data on current places in the Netherlands.[1] Rutte and IJsselstijn (2014) claim that most towns in the current Netherlands date back to before AD 1300. Therefore present day data can be used to recreate 16th-century habitation and to determine route-network persistence (Van Lanen et al., 2016). Maps from part 1 and

2 of the *Atlas van Nederland* (1984) made by Prof. dr. Renes, Histland[2] data and the Archaeological Landscapes Map of the Netherlands[3], were used to filter out settlements located in uncultivated lands (e.g. heathlands, younger reclamation areas) during the 16th century.

3.5. Historical roads in the Veluwe region

Historical road data for the Veluwe region were extracted from the AD 1600 route reconstructions by Horsten (2005) and the Topographic Military Maps 1850 (TMK 1850). Horsten (2005) reconstructed historical road networks for the period between the 16th and 19th century. This historical road atlas is primarily based on old maps, and reconstructs major interregional roads for the years ca. AD 1600, ca. 1800 and ca. 1848. Horsten (2005) choose these intervals since no detailed old maps are available dating before AD 1600, and after AD 1848 railway networks substituted many of these thoroughfares (Horsten, 2005). In the current study we used the earliest AD 1600 reconstruction for validation purposes (**Figure 3**).

The TMK 1850 first appeared between 1850 and 1864 (Van der Linden, 1973). The map constitutes the oldest nationwide map of the Netherlands on a 1:50,000 scale and was compiled for military purposes. Through thematic colouring the TMK 1850 provides a high-resolution overview of the mid-19th-century landscape. Since the map predates the massive industrialisation that began at the start of the 20th century, which radically changed many parts of the Dutch landscape, it provides invaluable information on past routes and other historical landscape elements that have since disappeared. Although also older, local maps are available, for example for the current province of Gelderland, these maps lack sufficient geographical precision to be used for this study.

3.6. Airborne Laser Scanning (ALS) data

In the Netherlands ALS data are the basis of the digital elevation model of the Netherlands, which is referred to as AHN. In 2003 the first generation of this model, the AHN-1, became available. This model uses a density of one height measurement per 1 to 16 m^2, resulting in a highest available grid-cell resolution of 5 m^2 (Brand et al., 2003; Swart, 2010). This raster is too crude for detailed analyses, which limits the usefulness of the AHN-1 on a local scale. To counter these limits a second generation of the AHN, the AHN-2, was presented in 2013 (Van der Zon, 2013).

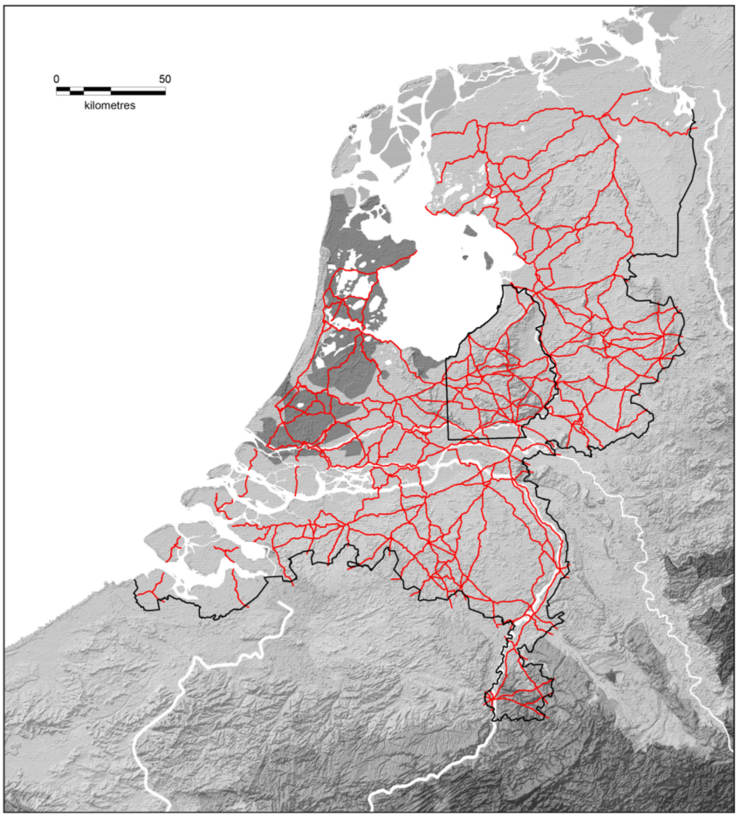


Figure 3: Road network in the Netherlands around AD 1600 reconstructed by Horsten (2005). In the present study only connection routes on the Veluwe (smaller framework) were included.

Table 1: ALS parameters used for route-network modelling.

Meta-information ALS	
ALS-Project	Actueel Hoogtebestand
Purpose of Scan	Water management
Time of Data Acquisition	April 2010
Point-distribution (pt. per sq. m)	6–10
Scanner Type	Riegl LMS-Q680i Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	36 m/s
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Yes
DTM-resolution	0.5 m
Interpolation method	Moving planes

The new dataset contains up-to-date measurements and a much higher resolution, with 6–10 measurements per m^2. For the sake of clarity, we use the (raw) ALS dataset and not the AHN models based on it. We defined the most important parameters of the ALS data for our route-network modelling in **Table 1**.

4. Method

The presented datasets were used to create a NFM showing local accessibility and to reconstruct route zones in the study area based on the network-friction method and LCP modelling.

4.1. The network-friction model (NFM)

The Veluwe NFM is based on the method presented by Van Lanen et al. (2015a; see Appendix A for more background information). It excludes data postdating AD 1600 and exclusively uses a 100 × 100 m grid cell resolution. The new model integrates environmental data in order to locate landscape obstacles that could limit accessibility (Sections 3.1–3.3). It covers the Veluwe region and immediate surroundings (**Figure 2**). It is important to include the latter since habitation in this area is largely clustered on the edges of the Veluwe. The model consists of 250,447 individual grid cells, roughly covering a region from the current city of Amersfoort in the west to the river IJssel in the east. Contrary to the NFM developed by Van Lanen et al. (2015a) which used a 500 × 500 m grid-cell resolution, the Veluwe NFM consists out of 100 × 100 m grid cells. Each cell was given a unique identifier and location coordinates. The Veluwe NFM consists of 14 data fields, covering all imported datasets (Sections 3.1–3.4 and **Table 2**). Point-location data such as settlements were not converted to the grid.

Table 2: Model design of the Veluwe network-friction model.

Field name	Description
Grid_ID	Unique identifier for each individual grid cell
Grid_ID500 m	Unique identifier grid cell in larger nationwide grid
Unit_AD1500	Unit of grid cell according to palaeogeographic map of AD 1500
Acc_AD1500_LA	Accessibility AD 1500 based on land factors
Unit_Arch_La	Unit of grid cell according to geomorphological map of the Netherlands
Arch_LA_GeomorfCode	Original geomorphological code map of the Netherlands
Acc_Arch_La_LA	Accessibility geomorphology based on land factors
Unit_Soil	Unit of grid cell according to soil map of the Netherlands
Code_soil	Original code from soil map
Acc_Soil_LA	Accessibility based on land-factors soil map
Unit_GW	Original code groundwater level map
Acc_GW	Accessibility based on groundwater reconstructions
Nf_AD1500_Sum	Combined network friction sum AD 1500
Nf_AD1500_AvG	Combined network friction average AD 1500

The Veluwe NFM is designed to reconstruct local accessibility, which is crucial for route orientation. Since within the NFM each grid cell can contain only one specific data unit per imported dataset (e.g. palaeogeography, geomorphology), based on archaeological and historical datasets we first imported traditionally accessible landscape units (e.g. high, dry areas; Appendix A). As a result, the NFM represents the maximum amount of possible movement corridors. In line with Van Lanen et al. (2015a) data was imported by overlaying the geoscientific datasets on the grid. The geometric intersections were imported using the following query in MapInfo 12.0.2:

Grid_ID.obj intersects Unit_External_Dataset_X.obj

In this SQL-query the location geometry (.obj) of each grid cell (Grid_ID) is compared to a specific landscape unit (e.g. peat, ice-pushed ridge) from each of the external datasets (Section 3). Grid cells intersecting these selected geoscientific polygons were then updated with the content of the external dataset. This import process was repeated for each of the geoscientific datasets. Next, within the geoscientific datasets accessibility values were given to each landscape unit following the classifications presented and substantiated

Table 3: Network-friction levels as defined by Van Lanen et al. (2015a).

Description	Network-friction value
Inaccessible	1
Poorly accessible	2
Moderately accessible	3
Reasonably accessible	4
Accessible	5

in Van Lanen et al. (2015a; Appendix A). These values were then used to calculate network-friction averages depicting local accessibility based on natural landscape settings showing obstacles and corridors for movement in the region (**Table 2**; Appendix A). Local accessibility was defined using five network friction levels: 1–5, ranging from inaccessible to accessible respectively (**Table 3**).

4.2. Modelling route zones based on network friction

NFM-route zones were modelled based on the Veluwe NFM and available settlement data (Section 3.4). Deviating from the original method by Van Lanen et al. (2015b; Appendix A) we only modelled land routes for the research area since no detailed overviews of water routes for the period around AD 1500 exist. Additionally, we excluded burial sites from our model, since the location rules surrounding these areas completely differ from the Roman and early-medieval periods. NFM-route zones reflect probable zones where people in the past frequently moved through the landscape, i.e. areas likely to contain roads, routes, paths and tracks. These route zones were modelled based on the assumption that they are largely defined by the wish to follow movement corridors (pull factors) and consequently to avoid movement obstacles (push factors). Following this hypothesis the shortest distance between two settlements following the best possible networks-friction values was calculated. These calculated lines were then converted to route zones with a width of 100 m (i.e. the highest possible accuracy level in a 100 × 100 m grid-cell resolution), which were used to compare with data on extracted hollow ways and known AD 1600 routes.

4.3. LCP model

In order to determine the applicability of the LCP method we selected four well-known historical roads running through the study area: 1) the *hessenweg* between Hattem and Voorthuizen, connecting Amsterdam over land to Germany, 2) the road between Arnhem and Harderwijk (*Harderwijkerweg*), 3) the route from Dieren to Barneveld and 4) the route between Apeldoorn and Voorthuizen.

Since in relative lowlands such as the Netherlands slope often is not a decisive factor (Verhagen, 2013) (Section 2), we have applied an LCP model incorporating three factors: terrain, slope and groundwater levels. Terrain values were based on two factors: the vicinity to water bodies and depressions in the landscape. We calculated the vicinity to water bodies by applying a threshold in the digital-terrain model (DTM) of the Veluwe based mainly on the largest water body in the region, the *Zuiderzee* (now IJsselmeer). Nevertheless, other water bodies like creeks were also taken into account when setting the threshold. Depressions in the landscape were also identified based on the DTM in combination with the suited tools in ArcGIS (fill and cut fill). These values were then combined into one GIS layer reflecting the lower, wetter areas. All remaining areas were classified as higher grounds. In order to make them suitable for LCP modelling in ArcGIS, the values (costs) of two classes were based on the terrain coefficients of Soule and Goldman (1972).

In our LCP calculations, terrain, slope and groundwater levels have (changeable) weight values, which serve as input for the cost path calculation tool in ArcGIS. This allows us to calculate LCP routes between two places and to compare these trajectories with data on historical routes. In order to optimize the comparison with the NFM-route zones we selected routes that cross the study area in different directions.

4.4. ALS extraction

Remnants of cart tracks and hollow ways were extracted using ALS data from the Veluwe. Based on the extraction model developed by Vletter (2014) a semi-automatic extraction was executed on the data from the Veluwe (Section 3.6). The micro topography was visualized in grey scales using the *openness* module in OPALS developed by the Technical University of Vienna (Yokoyama et al., 2002; Pfeifer et al., 2014). Although some visualization techniques might provide better results for the reconstruction of microrelief in flat areas (Hesse, 2016), we chose for *openness* because other techniques are less suited for extraction purposes. We used openness in an extraction model created in the software plug-in Feature Analyst (FA) in ArcGIS. The original extraction model for the Leitha area was adjusted to fit the conditions of the research area. Since it is difficult to differentiate between man-made linear features, such as (historical) roads and paths made by cart and wagons, and natural linear features, some additional manual mapping based on expert judgement was needed. Further, the merge and dissolve tools in ArcGIS were used to create road sections. In order to allow a comparison between these ALS-extracted hollow ways (which can spread over hundreds of meters) and our NFM and LCP routes, we drew a 'centre line' through the extracted zones.

4.5. Modelling validation through comparison data

In order to determine the applicability and usefulness of the Veluwe NFM and LCP models we compared the modelling outcomes with several other datasets on route networks in our study area. First, the NFM and LCP outcomes were compared with data on known routes in the study area through a comparison with the TMK 1850, the AD 1600 route network compiled by Horsten (2005), and the extracted ALS route data. Second, we used the NFM to calculate the correspondence between local accessibility values based on landscape setting and the LCP model, routes visible on the TMK 1850, the AD 1600 route network, and extracted ALS route data.

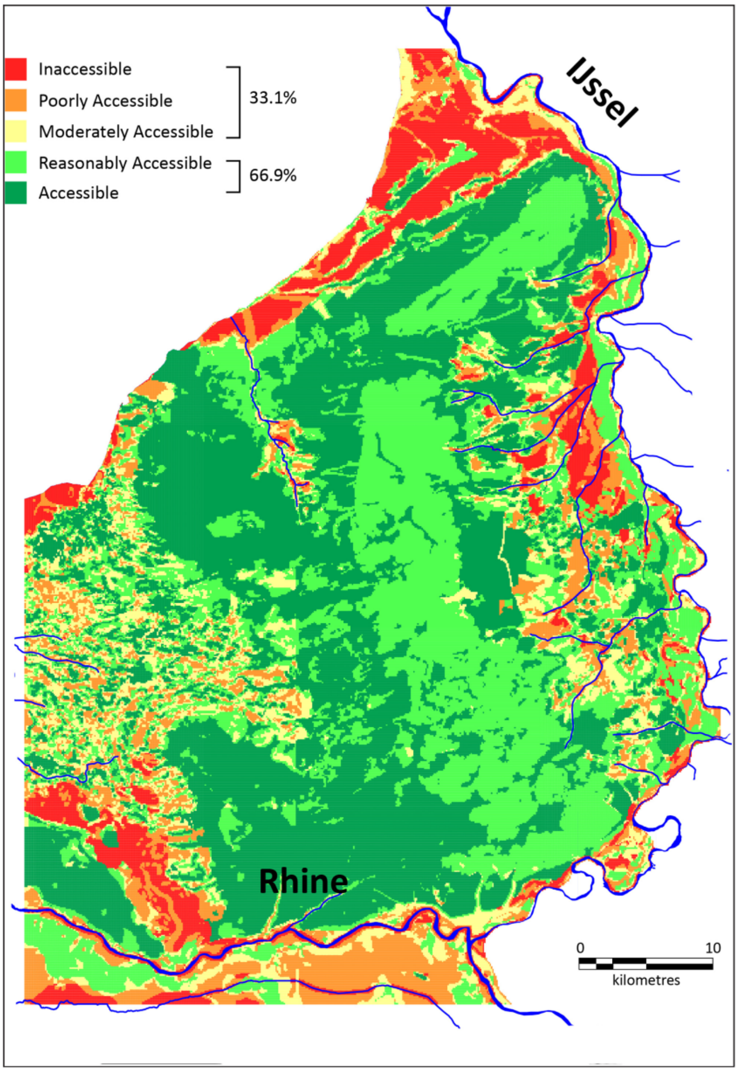


Figure 4: Network-friction map of the research area around AD 1500. Probable movement corridors are show dark green, and obstacles in red. Additional percentages of poorly and well-accessible areas are given. Major rivers (in blue) bordering the research area, the river IJssel in the east and the river Rhine to south.

5. Results

5.1. Network-friction map Veluwe ca. AD 1500

Based on the network-friction values the research area is divided into several corridors and obstacles for movement (**Figure 4**). The central part of the Veluwe appears to have been relatively well accessible. This is in contrast to the eastern and southern parts, where the rivers Rhine and IJssel (and their floodplains) constituted clear obstacles. In these parts the location of bridges and ferries must have determined the orientation of routes. Several stream valleys ran from the central part of the Veluwe to the edges of the research area. In the lower parts of these valleys the occurrence of peat and clay severely must have hampered movement, especially in the western part of the research area (**Figure 4**). Accessibility in the north of the research area was negatively influenced by a large peat area and the water from the *Zuiderzee*.

5.2. NFM route zones

Route zones were modelled using settlement distribution around AD 1600 and the method presented by Van Lanen et al. (2015b; Appendix A) (**Figure 5**). Results show that the majority of the modelled route zones are located in the western part of the research area. Only a few routes

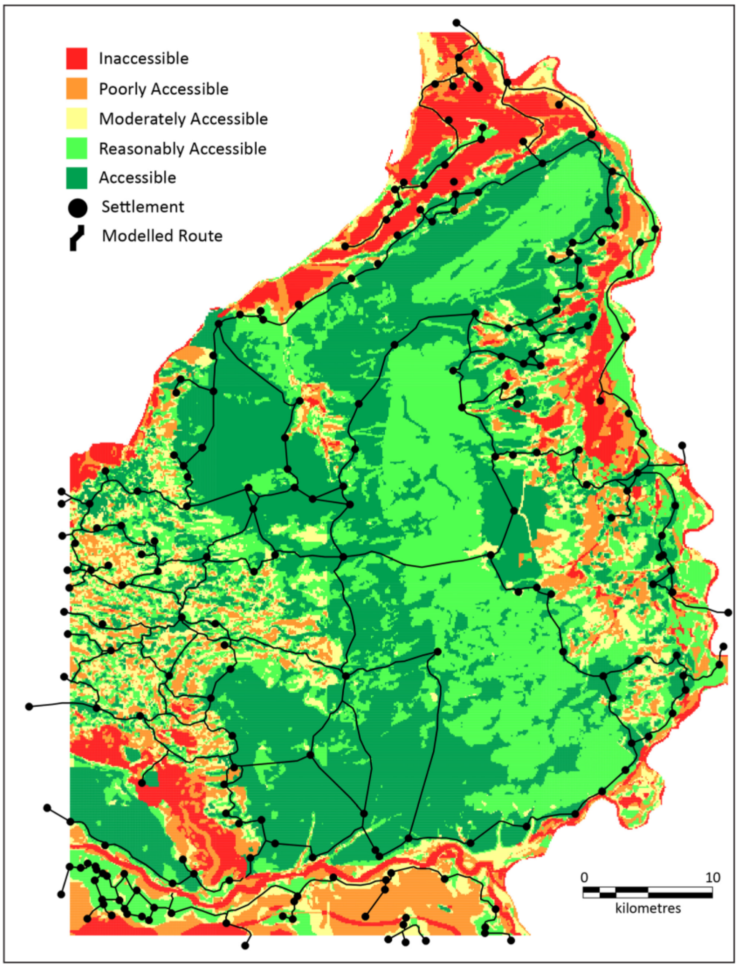


Figure 5: Route network based on the network-friction approach in the Veluwe area around AD 1500.

connected settlements east and west from the higher push moraine, which seems to have formed an obstacle. Route zones in the western and eastern parts of the study area clearly were influenced by local soil conditions such as the presence of peat and by the vicinity of waterways (**Figure 5**).

5.3. LCP routes

Based on the LCP model we were able to calculate 4 LCP routes (**Figure 6**). The modelled routes point towards an especially strong influence of the terrain factor on route-network orientation. In general, groundwater levels and slope appear to have been of less influence. The LCP route between Arnhem and Harderwijk (*Harderwijkerweg*) is an exception, since here multiple groundwater-level differences influenced route orientation. The factor slope appears to have been least influential on the routes in the area. Therefore, the LCP model allows us to calculate routes and to determine the relative influence of specific landscape factors on route-network development. The flexibility of the model, i.e. the possibility of assigning different or new weight values to individual factors, allows us to easily expand or change the focus of the model.

5.4. ALS-extracted routes

Based on the ALS extraction we were able to locate a high number of hollow ways (**Figure 7**). Primarily these could be extracted for the sandy regions, with the exception of the sand-blown areas where past roads and paths probably are covered. The western and eastern parts of the study area show limited signs of hollow ways, which is probably due to different soil conditions (mainly peat and clay) in these parts. Looking at the directionality of the extracted hollow ways, they can be divided into two main groups: 1) a high number of west-east connections crossing the push moraine; 2) a lower number of north-south connections

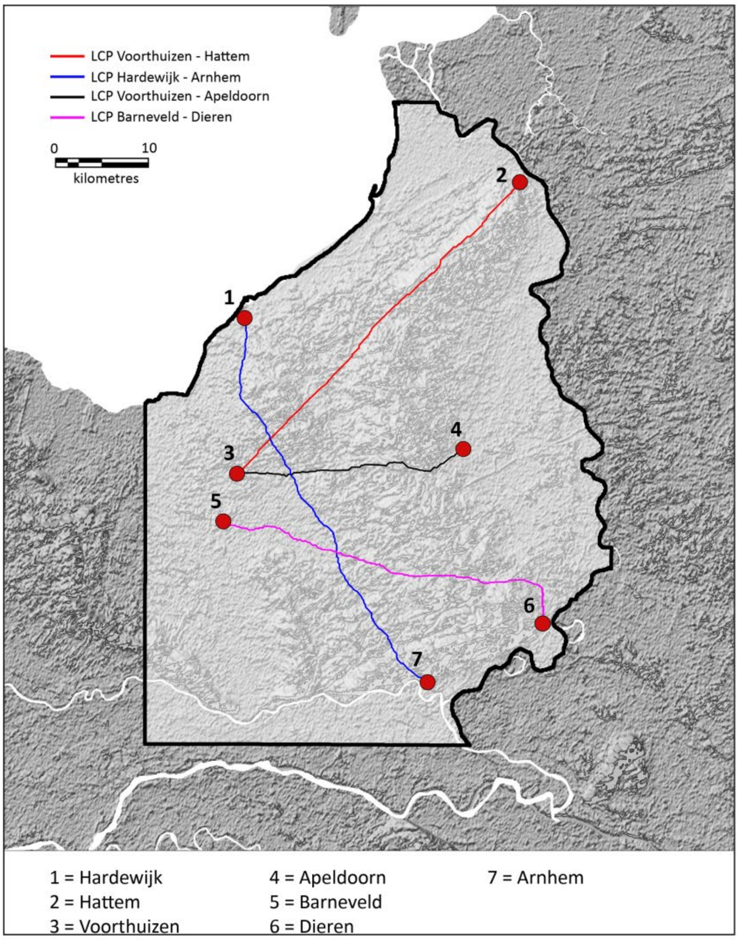


Figure 6: Least-cost path (LCP) calculated routes on the Veluwe. Four routes were preselected and modelled: 1) the LCP running from Voorthuizen to Hattem, 2) LCP running from Harderwijk to Arnhem, 3) LCP running from Voorthuizen to Apeldoorn and 4) the LCP running between Barneveld and Dieren.

descending from the push moraine to the coastal plane, especially in the northern part of the study area.

6. Validation through comparison data

In order to determine the applicability of the NFM and LCP models we compared the outcomes with existing route-network datasets pertaining to the study area. As comparison data we used the ALS-extracted hollow ways, routes visible on the TMK 1850, and the AD 1600 route reconstruction by Horsten (2005).

6.1. Validating the NFM

6.1.1. NFM accessibility

In order to determine the usefulness of NFM accessibility calculations, we computed the agreement between the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850 routes (**Table 4**). For the comparison datasets we determined the absolute number (in metres/grid cells) and the surface percentages of routes located within either well-accessible or poorly-accessible areas (NFM values 4–5 and 1–3, respectively). For each of the comparison datasets a convincing agreement between local accessibility and the occurrence of routes can be identified, showing that a combined landscape setting clearly influences route-network development (**Table 4**). The relative high number of ALS-extracted hollow ways located in well-accessible areas (99.0%) is best explained by preservation circumstances, i.e. the hollow ways that still remain today are best preserved in higher and dryer areas, which often also reflect the well-accessible movement corridors. For the AD 1600 network, some routes ran through less-accessible areas, mainly near the rivers in the south and northeast of the study area (**Figure 7**). Although the lowest agreement of the TMK-

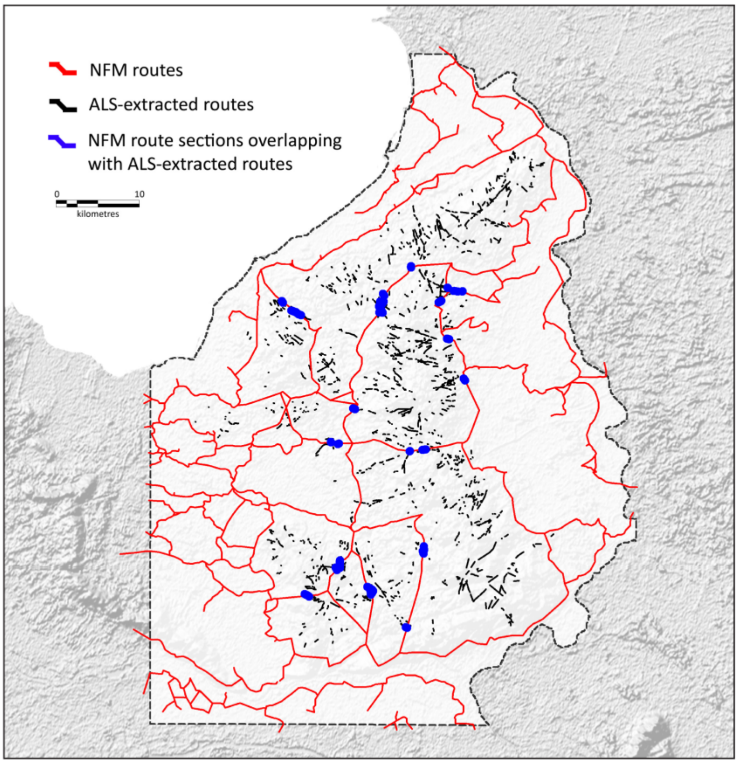


Figure 7: Hollow ways (in black) extracted from airborne laser scanner data. Sections where these hollow ways correspond with the calculated NFM-route zones (red) are highlighted in blue.

Table 4: Agreement between local accessibility based on network friction, the ALS-extracted hollow ways and the AD 1600 route network.

Description	NFM value <= 3	NFM value >= 3	% NFM value <= 3	% NFM value >= 3
ALS-extracted hollow ways (in metres)	234	269247	1.0%	99.0%
AD 1600 route network (in square metres)	1397	6283	18.2%	81.8%
TMK-1850 routes (n grid cells)	35359	117061	23.2%	76.8%

1850 routes, being still quite high at 76.8%, ran through well-accessible areas, it should be noted that in the entire NFM 66.9% of the grid cells reflect well-accessible areas (n = 167,494).

6.1.2. NFM-route zones

The calculated NFM-route zones (100 m wide) were compared with the ALS-extracted hollow ways, the AD 1600 route network, and routes shown on the TMK 1850 (**Table 5**). For each of the comparison datasets we determined the surface area of routes corresponding with the NFM-route zones. Results show that only 2.3% of the ALS-extracted hollow ways are located in NFM-route zones (**Figure 8**). This might be explained by the fact that hollow ways reflect a different chronological time frame or a different type of connection (i.e. more local paths within the network). A strong argument for this interpretation is the perpendicular orientation of the NFM-route zones and the ALS-extracted hollow ways. Agreement with the AD 1600 network is notably higher: 29.2% (**Table 5**; **Figure 9**). Looking at the distribution of the overlap between the two networks, agreement in the lower parts of the study area is relatively high, predominantly the western part. Additionally, the

Table 5: Agreement between route zones (100 m wide) based on settlement data and network friction, and the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850.

Description	No agreement with route zone (in km²)	Agreement with route zone (in km²)	% Not correlating with route zone	% Correlating with route zones
ALS-extracted hollow ways (in km²)	1570	37	97.6%	2.4%
AD 1600 route network (in km²)	44.8	18.5	70.8%	29.2%
TMK 1850 routes (in km)	782.2	313.2	60.0%	40.0%

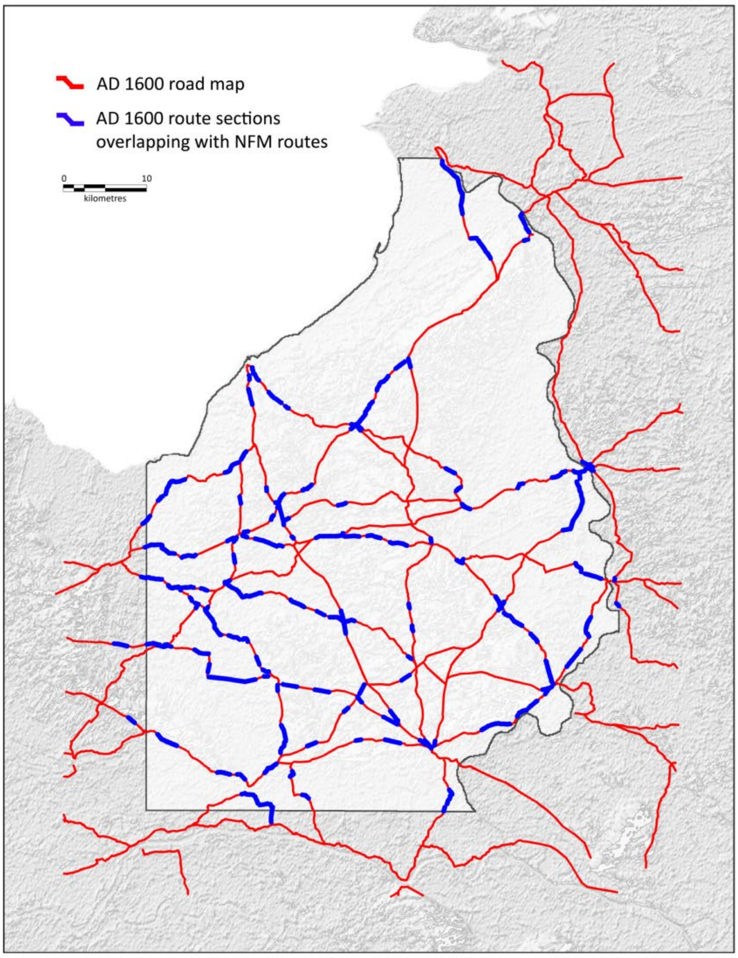


Figure 8: AD 1600 road-map sections overlapping with NFM routes (in blue).

dissemination of the overlapping route sections visually points towards a higher agreement when increasing route-zone width, i.e. correlating route sections covering the majority of the network (**Figure 9**). The largest deviation between the two networks appears to be located on top of the largest push moraine in the area. Here the NFM fails to reconstruct the thoroughfare reconstructed by Horsten (2005) running on top of

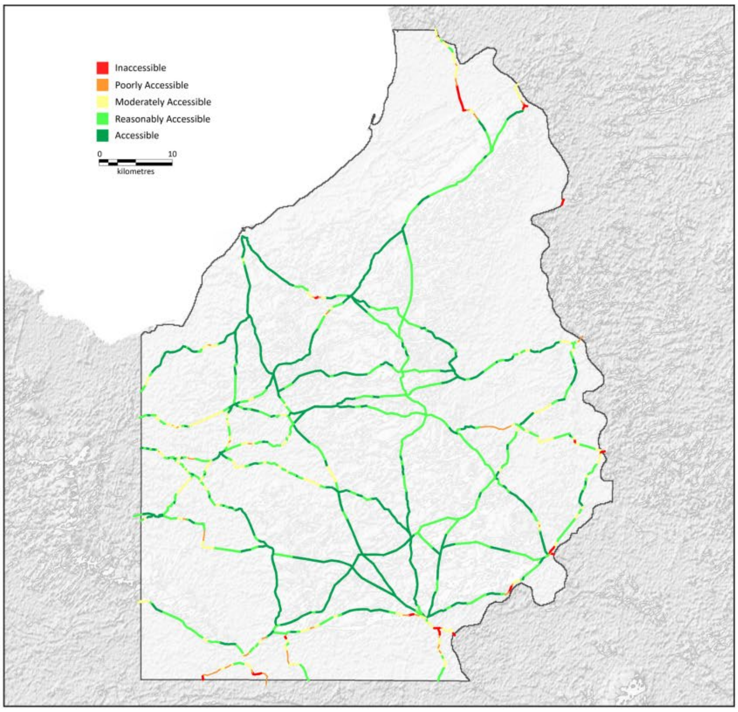


Figure 9: Local-accessibility values integrated in the AD 1600-route network. For each section within the AD 1600 route network local accessibility values based on network friction is given. Green areas depict well-accessible areas, yellow, orange and red poorly accessible regions.

Table 6: Agreement between LCP-calculated routes (100 m wide route zone), the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850.

Description	Outside route zone	Inside route zone	% Outside route zones	% Inside route zone
ALS-extracted hollow ways (in metres)	150314	11292	92.7%	7.3%
AD 1600 route network (in metres)	147223	14383	91.1%	8.9%
TMK 1850 routes (in metres)	108600	53006	67.2%	32.8%

this moraine, which is best explained by more complex cultural variables (e.g. socio-economic) behind the development of this route. Comparison results are best with the TMK 1850, showing that 40.0% of the routes on this map correspond with the calculated NFM-route zones. It should, however, be noted that the TMK 1850 depicts a much higher number of routes than the other two comparison datasets.

6.2. Validating the LCP model

The results of our LCP model, routes converted to 100 m-wide zones, were compared to the same datasets as those that were used in the validation of the NFM (**Table 6**). Given the agreement between the LCP routes and the ALS-extracted hollow ways, only 7.3% of the hollow ways correspond to the LCP routes. This relatively minor overlap might be explained by the partial disappearance of these routes over time. This is supported by the fact that 53.0% of the extracted hollow ways correspond with routes shown on the TMK 1850, which suggests that local hollow ways are better preserved than long-distance ones. The agreement between the LCP routes and the AD 1600 network is slightly higher than with the ALS-extracted hollow ways: 8.9% (**Table 6**). This still relatively minor overlap is best explained by the fact that Horsten (2005) in his overview did not reconstruct the complete route network and only focussed on the most important connections. Additionally, the very small applied route zone of 100 m and the incompleteness of the model further hamper results. Since we selected the LCP routes based on their confirmed existence in historical sources, agreement with the TMK 1850 is (not surprisingly) the highest: 32.8% (**Table 6**). It should, however, be noted that the TMK 1850 shows more roads and paths than the other comparison datasets. Therefore, more alternative routes are likely to fall into the 100 m route zone and variations between the individuals LCP routes are visible (for more background data see, Appendix B).

7. Discussion

7.1. Network-friction method

The high percentage of overlap between high NFM accessibility and the location of ALS-extracted hollow ways and AD 1600 routes, 99.0% and 81.8% respectively (**Table 4**), point towards a strong link between route networks and (combined) landscape setting. Although the NFM does not predict the location of individual hollow ways it does calculate regions where remnants of these landscape features can be expected. This predictive potential of the NFM could be further increased by incorporating detailed information on past-drift sands into the model. It should however be noted that these strong agreements potentially are positively influenced by the general high level of accessibility of the Veluwe region (66.9% well-accessible areas). Therefore to further test the applicability of the network-friction approach a similar NFM should be applied on more dynamic lowland areas, such as river areas.

In contrast, route zones calculated through the NFM show relatively little agreement with the ALS-extracted hollow ways and AD 1600 routes. There are various explanations for the minor overlap between NFM-route zones and the ALS-extracted hollow ways (2.3%; **Table 5**). First, scale differences between the two methods most likely play a role. Where the NFM-route zones were designed to model supraregional connections, the ALS-extracted hollow ways (based on orientation) appear to reflect a more local network of paths and tracks (Section 6.1). In order to determine whether the NFM can be used to also model these local paths and tracks, grid-cell resolution and especially input-data resolution should be greatly increased in the future. Second, the NFM specifically was designed to reconstruct route zones around AD 1500. The ALS extracted hollow ways lack chronological differentiation and can only be dated relatively. Therefore part of the ALS-extracted hollow ways could actually reflect preceding or postdating time frames. Third, both the NFM and the ALS-extracted hollow ways only reflect remnants of the old route networks. ALS data is only useful for locations where features of these routes and paths are still preserved in the landscape, and preservation strongly depends on geomorphological stability (non-dynamic sandy areas) and cultural conditions (e.g. non densely populated or cultivated areas). Fourth, the current NFM-route zones currently lack a differentiation between different types of routes (e.g. route hierarchy); adding such detailed (historical) data to the model would probably benefit modelling results further.

Agreement between the NFM-route zones and the AD 1600 route network is much higher, but still only 29.2% (**Table 5**). This is best explained by the spatial resolution of the NFM and the method behind route-zone calculations. First, in our agreement calculations we used 100 m wide route zones, despite the fact that many of these zones could actually be several hundreds of metres wide (Section 2). In this respect, the overlap percentage reflects a minimum amount of corresponding routes and actual overlap percentages might be higher. Second, NFM-route zones were designed to reconstruct large-scale connection transport zones (Section 2). The method was not designed to model routes on a detailed regional scale, which would require a more dense network with multiple connections between nodes. In order to determine the full potential of the network-friction method, NFM-route zones could incorporate more detailed network analyses and LCP calculations in combination with more detailed geoscientific data. **Figure 8**, however, shows that despite the low overlap percentage between the NFM-route zones and the AD 1600 network, many parts do line up, and increasing route zone widths would probably lead to much higher agreements. The most notable exception is the route running over the high push moraine in the centre of the study area. Here, the NFM fails to calculate a route zone since no nearby settlement data are available. The probably socio-economic origin of this route reconstructed by Horsten (2005) fundamentally differs from the (Roman and early-medieval) variables defined by Van Lanen et al. (2015b). In order to also model these kinds of routes, other input variables, specifically designed for this historical period, should be developed for the NFM.

One of the aims of the current study was to determine the applicability of the network-friction method on a more detailed, regional scale and a different historical period. The method originally was designed specifically for the Roman period and Early Middle Ages, but this study shows that the approach does have potential in reconstructing more recent route networks. Since the NFM is an accumulative model the number of input datasets can be potentially endless, making the model flexible and especially accurate in reconstructing past accessibility based on landscape prerequisites. Although the models' resolution was increased by decreasing grid-cell size from 500 × 500 m to 100 × 100 m, agreement percentages (**Table 5**) show that NFM route-zone calculations probably benefit from a) more detailed geoscientific input data (<1:50,000), including high-resolution vegetation reconstructions, and b) modelling techniques from network and least cost path analyses.

7.2. Least-cost path method

The LCP-calculated routes agree best with the TMK 1850 dataset. This is not surprising, because a) this map shows a much higher number of (alternative) roads and paths and b) the LCP calculated routes reflect preselected trajectories of routes known to be in use during the 19th century (Section 4.3; Appendix B). Based on the LCP model it has become clear that terrain appears to have been the forcing factor in route-network orientation, followed by groundwater levels and slope. However, the model also shows that forcing factors can differ per individual route section (Appendix B). Consequently there is not one factor dominating route orientation in the Veluwe and each LCP route actually should be investigated individually. For example, avoiding lower, wet areas was especially important for route sections between Arnhem – Harderwijk which ran on the west brink of the push moraine and Hattem – Voorthuizen near the coast. If merely slope would have been the forcing factor for these routes, these lower areas would have been best suited for the network and agreement with the TMK 1850 even lower. In some cases, like the route Dieren – Barneveld the forcing factor is difficult to assess and cultural factors especially appear to have been in play (Appendix B). The diversity in forcing factors do point towards the need of applying flexible modelling which incorporates changing local accessibility settings based on a multitude of datasets.

The LCP model applied in this paper calculates routes based on weight values derived from terrain, slope and groundwater-level factors. Terrain coefficients were quantified based on scientific data (Soule and Goldman, 1972). However, many of other weight values were determined based on expert judgement. For example, in determining the terrain factor, threshold values were determined based on a combination of the soil map, DTM and the TMK 1850 (Appendix B). Therefore these threshold values depict the present-day situation and may differ slightly from the historical situation around AD 1500. The same bias applies to the factor slope, which was calculated based on current elevation data in the study area. It is currently impossible to determine the exact differences between the historical and present-day situation. Therefore the LCP model would benefit from more detailed geoscientific input data reflecting the period around AD 1500.

7.3. Methodological integration

This study shows that route-network modelling using GIS improves our understanding of past route networks in the Veluwe region. Agreement results are best for the network-friction approach. Through the accumulative nature, the NFM integrates multiple geoscientific datasets and provides dynamic local accessibility values for entire route trajectories, which allows to compensate for changing forcing factors. Route zones calculated by the NFM appear to mainly reflect thoroughfares in the study area. These NFM-route zones show the best agreement in the lower areas where movement corridors are most pronounced. Through the integration of multiple datasets the NFM also allows to locate omissions in other datasets. For example by comparing the NFM with the AD 1600 network we were able to locate areas with a high-accessibility level and an abundance of settlements and therefore increased likelihood of route occurrence not reconstructed by Horsten (2005) (**Figure 10**). Agreement results for the LCP model were lower compared to the NFM but did show the necessity of incorporating multiple landscape variables when calculating individual LCP

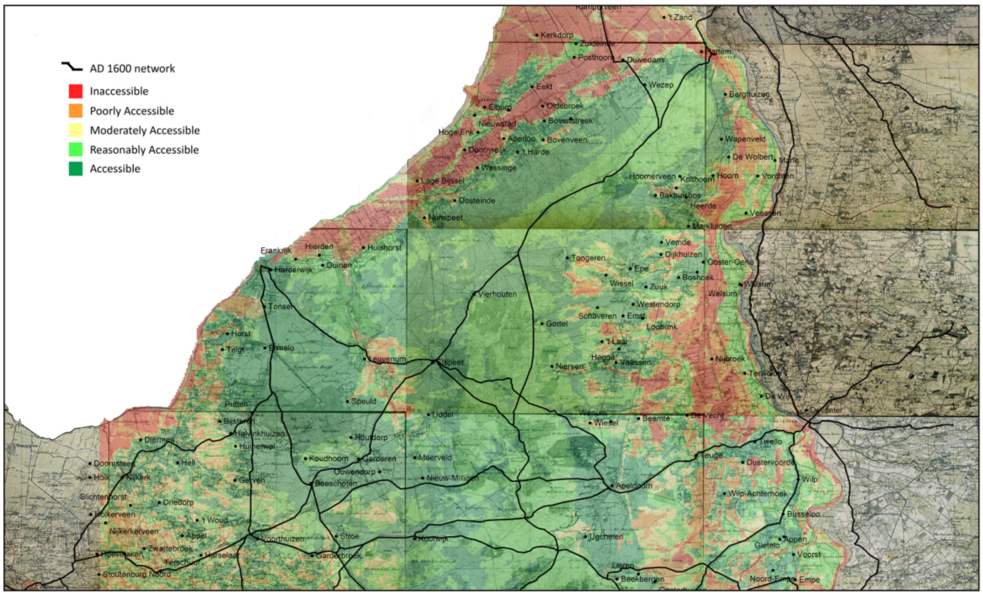


Figure 10: Network-friction map overlaid on the TMK 1850 and the AD 1600 road map by Horsten (2005) for the northwestern part of the study area. In this section, for example, it is clearly visible that not all AD 1600 routes connect settlements, reflecting the fragmentary state of AD 1600 route network. Based on the NFM, movement corridors are reconstructed which can point towards probable missing route-zone connections. For example connecting thoroughfares can be expected running from west to east in the northern part of the study area.

routes, i.e. different sections within one route can have different forcing factors. Both modelling approaches show potential for route-network modelling on the Veluwe and could be further integrated in the future. Where network friction provides dynamic local accessibility values, the LCP modelling allows for the calculation of specific movement conditions which could benefit the NFM-route zone modelling on this more detailed regional scale in order to also include more local paths and tracks in less pronounced movement corridors.

8. Conclusion

In this study we have applied and compared two different route-network modelling techniques in order to optimally reconstruct route networks around AD 1500 in the Veluwe region. We were able to determine that the central part of the study area appears to have been relatively well accessible. In the western, lower parts the presence of peat and clay must have limited route options, resulting in few and narrow movement corridors. To the south and east accessibility was bound by the rivers Rhine and IJssel and to the north by the sea (Zuiderzee). Although the study area in general is well accessible, routes appear to have mainly run along the borders and not through its central part. This is underlined by the lack of settlements in this area. Consequently, east-west routes predominantly appear to have run alongside, and not across, the largest push moraine.

Both the NFM and LCP model we have applied in this paper successfully modelled parts of the route networks around AD 1500. Agreement results with comparison datasets are highest for the NFM, which shows great potential in reconstructing past local accessibility and thoroughfares based on integrating multiple datasets. The NFM however has difficulties reconstructing more local, micro-regional connections. This study shows that it is possible to increase the grid-cell resolution of a NFM to 100 × 100 m, but that much is to be gained by increasing the resolution of geoscientific and cultural input data. The more traditional LCP model was especially successful in determining different forcing factors behind route development, but agreement results with comparison data on route network are generally low. However, the model does show the need for incorporating multiple factors during LCP calculations. Both models prove quite useful for route-network modelling on a regional scale, reconstructing parts of past networks. Because regional and micro-regional route networks are characterized by multi-scale variability, i.e. supraregional, regional and micro-regional connections are all entwined, studying these spatial structures requires a more integrated multi-proxy approach.

Notes

[1] For more information on OpenStreet data and mapping, see www.openstreetmap.org (accessed 17-11-2015).

[2] Histland contains data on the reclamation and dynamics of the Dutch landscape. For more information, see http://landschapinnederland.nl/bronnen-en-kaarten/histland (accessed 17-11-2015).

[3] This dataset was developed in 2015 by the Cultural Heritage Agency of the Netherland. See http://archeologieinnederland.nl/bronnen-en-kaarten/archeologische-landschappenkaart (accessed on 17-11-2015).

Additional Files

The additional files for this article can be found as follows:

- **Appendix A.** Network friction. DOI: https://doi.org/10.16993/rl.35.s1
- **Appendix B.** Least-cost path (LCP) calculations. DOI: https://doi.org/10.16993/rl.35.s2

Acknowledgements

This collaborative study was carried as part of the research program 'The Dark Age of the Lowlands in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000', which is funded by the Netherlands Organisation for Scientific Research (NWO, section Humanities; 2012–2018; project number 360-60-110). It is also part of the Initiative College Archaeological Prospection (IC-Archpro) of the University of Vienna. The authors would like to thank University Prof. Mag. Dr. Michael Doneas, Prof. Dr. Esther Jansma, Dr. Bert J. Groenewoudt, and Prof. Dr. Theo Spek for their comments on earlier drafts of the paper.

Competing Interests

The authors have no competing interests to declare.

Authors Information

Willem F. Vletter and Rowin J. van Lanen are contributed equally to this work.

References

Bakker, J. A. (1976). On the possibility of reconstruction roads from the TRB period. *Berichten van de Rijksdienst voor Oudheidkundig Bodemonderzoek, 26*, 63–91.

Bell, T. & **Lock, G.** (2000). Topography and cultural influences on walking the Ridgeway in later prehistoric times. Lock, G. R. (Eds.), *Beyond the map: archaeology and spatial technologies*, 85–100. IOS Press.

Bourgeois, Q. P. J. (2013). *Monuments on the horizon.* (Dissertation thesis, University of Leiden). Sidestone press.

Brand, G. B. M., Crombaghs, M. J. E., Oude Elberink, S. J., Brügelmann, R. & de Min, E. J. (2003). *Predisiebeschrijving AHN 2002*, Rijkswaterstaat AGI.

Citter, C. (2012). Modelli predittivi e archeologia postclassica: Vecchi strumenti e nuove prospettive. Redi, F. & Forgione, A. (Eds.), *Atti del VI convegno nazionale della SAMI*, 3–6. L'Aquila, 2012, Firenze: Edizioni All'Insegna del Giglio.

De Bakker, H. & **Schelling, J.** (1989). *Systeem van bodemclassificatie voor Nederland. De hogere niveaus.* Wageningen, Pudoc.

Deeben, J. H. C. (Eds.), (2008). De Indicatieve Kaart van Archeologische Waarden, derde generatie. *Rapportage Archeologische Monumentenzorg,* 155. Amersfoort.

De Vries, F., de Groot, W. J. M., Hoogerland, T. & **Denneboom, J.** (2003). De bodemkaart van Nederland digitaal; Toelichting bij inhoud, actualiteit en methodiek en korte beschrijving van additionele informatie. *Alterra-rapport,* 81. Wageningen, Alterra Research Instituut voor de Groene Ruimte.

Doneus, M. (2013). Die hinterlassene Landschaft. Prospektion und Interpretation in der Landschaftsarchäologie. *Mitteilungen der Prähistorischen Kommission,* 78. Vienna, Verl. D. Österr. Akad. D. Wisss. DOI: https://doi.org/10.2307/j.ctt1vw0qcb

Fovet, É. & Zakšek, K. (2014). Path Network Modelling and network of agglomerated settlements: A case study in Languedoc (Southeastern France). Polla, S. & Verhagen, Ph. (Eds.), *Computational Approaches to the Study of Movement in Archaeology. Theory, Practice and Interpretation of Factors and Effects of Long-term Landscape Formation and Transformation,* 43–72. Berlin, de Gruyter.

Gietl, R., Doneus, M. & Fera, M. (2008). Cost Distance Analysis in an Alpine Environment: Comparison of Different Cost Surface Modules. Posluschny, A., Lambers, K. & Herzog, I. (Eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology* (*CAA*), 10, 336–341. Berlin, Germany, April 2–6, 2007 (Kolloquien zur Vor- und Frühgeschichte, Bonn, Dr Rudolf Habelt GmbH).

Herzog, I. (2013). Theory and Practice of Cost Functions. Contreras, F., Farjas, M. & Melero, F. J. (Eds.), *Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology.* 375–282. Granada, Spain, April 2010. BAR International Series 2494. Oxford: Archaeopress.

Herzog, I. & Posluschny, A. (2011). Tilt – Slope-Dependent Least Cost Path Calculations Revisited. Jerem, E., Redő, F. & Szeverényi, V. (Eds.). *On the Road to Reconstructing the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 36th International Conference,* 212–218. Budapest, April 2–6, 2008, Budapest: Archeaeolingua.

Hesse, R. (2016). Visualisierung hochauflösender digitaler Geländemodelle mit LiVT. Lieberwirth, U. & Herzog, I. (Eds.), *3D-Anwendungen in der Archäologie. Computeranwendungen und quantitative Methoden in der Archäologie. Workshop der AG CAA und des Exzellenzclusters Topoi 2013,* 109–128. Berlin: Edition Topoi.

Horsten, F. H. (2005). *Doorgaande wegen in Nederland, 16etot 19E eeuw. Een historische wegenatlas.* (Dissertation thesis, University of Utrecht, Utrecht). Amsterdam: Aksant.

Howey, M. C. L. (2011). Multiple pathways across past landscapes: Circuit theory as a complementary geospatial method to least-cost path for modeling past movement. *Journal of Archaeological Science, 38,* 2523–2535. DOI: https://doi.org/10.1016/j.jas.2011.03.024

Jiang, H. & **Eastman, J. R.** (2000). Application of fuzzy measures in multi-criteria evaluation in GIS. *International Journal of Geographical Information Science, 14*(2), 173–184. DOI: https://doi.org/10.1080/136588100240903

Koomen, A. J. M. & **Excaltus, R. P.** (2003). De vervlakking van Nederland: naar een gaafheidkaart voor reliëf en bodem, *Alterra-rapport 740.* Alterra research institute, Wageningen.

Koomen, A. J. M. & **Maas, G. J.** (2004). Geomorfologische Kaart Nederland (GKN); Achtergronddocument bij het landsdekkende digitale bestand. *Alterra-rapport.* 1039. Wageningen: Alterra research institute.

Llobera, M. (2000). Understanding movement: A pilot model towards the sociology of movement. Lock, G. R. (Ed.), *Beyond the Map: Archaeology and Spatial Technologies,* 65–84. Amsterdam: IOS Press.

Murietta-Flores, P. (2010). Traveling in a Prehistoric Landscape: Exploring the Influences that Shaped Human Movement. *Making History Interactive. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America,* 249–267. March 22–26, 2009. Oxford: Archaeopress.

Pfeifer, N., Mandlburger, G., Otepka, J. & **Karel, W.** (2014). OPALS – A framework for Airborne Laser Scanning data analysis. *Computers, Environment and Urban Systems, 45,* 125–136. DOI: https://doi.org/10.1016/j.compenvurbsys.2013.11.002

Polla, S. & **Verhagen, J. W. H. P.** (Eds.), (2014). *Computational Approaches to the Study of Movement in Archaeology. Theory, Practice and Interpretation of Factors and Effects of Long-term Landscape Formation and Transformation.* Berlin, de Gruyter. DOI: https://doi.org/10.1515/9783110288384

Renes, H. (1984). *Atlas van Nederland. Deel 2, Bewoningsgeschiedenis.* The Hague: Staatsdrukkerij.

Rensink, E., Weerts, H. J. T., Weerts, Kosian, M. C., Feiken, H. & **Smit, B. I.** (2017). The Archaeological Landscapes Map of the Netherlands. A new map for inventory and analysis at the archaeology-landscape interface. Lauwerier, R. C. G. M., Eerden, J. M., Groenewoudt, B. J., Lascaris, M. A., Rensink, E., Smit, B. I., Speleers, B. P. & Van Doesburg, J. (Eds.), *Knowledge for informed choices. Tools for a more effective and efficient selection of valuable archaeology in the Netherlands. Nederlandse Archeologische Rapporten (NAR). 55,* 36–47.

Rutte, R. J. & **IJsselstijn, M.** (2014). 1000–1500. Stadswording aan waterwegen: De grote stedenboom *Atlas van de verstedelijking in Nederland. 1000 jaar ruimtelijke ontwikkeling.* 170–185. Bussum: Thoth.

Soule, R. G. & **Goldman, R. F.** (1972). Terrain coefficients for Energy Cost Predition. *Journal of Applied Physiology, 32*(5), 706–708. DOI: https://doi.org/10.1152/jappl.1972.32.5.706

Steur, G. G. G. & **Heijink, W.** (Eds.), (1991). *Bodemkaart van Nederland. Schaal 1:50000. Algemene begrippen en indelingen.* Wageningen.

Swart, L. M. Th. (2010). How the up to date height model of the Netherlands (AHN) became a massive point data cloud. *Management of Massive Point Cloud Data: Wet and Dry.* Delft: Nederlandse commissie voor Geodesie.

Van der Gaast, J. W. J., Vroon, H. R. J. & **Massop, H. Th. L.** (2010). Grondwaterregime op basis van karteerbare kenmerken. *STOWA rapportnummer, 41.* Amersfoort: STOWA.

Van der Linden, J. A. (1973). *Topographische en Militaire kaart van het Koningrijk der Nederlanden.* Bussum.

Van der Zon, N. (2013). *Kwaliteitsdocument AHN2.* Delft: Rijkswaterstaat en Waterschappen.

Van Lanen, R. J. (2016). Historische routes in Nederland. Een multidisciplinaire zoektocht naar verdwenen en langdurig gebruikte routetrajecten, *Tijdschrift voor Historische Geografie (THG),* 12–29. jaargang 1, 1, Verloren. DOI: https://doi.org/10.1007/s12520-016-0431-z

Van Lanen, R. J. (2017). Changing ways. Patterns of connectivity, habitation and persistence in Northwest European lowlands during the first millennium AD, PhD dissertation Utrecht University. *Utrecht Studies in Earth Sciences (USES), 137.* Ipskamp.

Van Lanen, R. J., Groenewoudt, B. J., Spek, T. & **Jansma, E.** (2016). Route persistence. Modelling and quantifying historical route-network stability from the Roman period to Early-Modern Times (AD 100 1600): A case study from the Netherlands, *Archaeol Anthropol Sci.* DOI: https://doi.org/10.1007/s12520–016–0431-z

Van Lanen, R. J., Kosian, M. C., Groenewoudt, B. J. & **Jansma, E.** (2015b). Best travel options: Modelling Roman and early-medieval routes in the Netherlands using a multi-proxy approach. *Journal of Archaeological Science: Reports (JASR), 3,* 144–159. DOI: https://doi.org/10.1016/j.jasrep.2015.05.024

Van Lanen, R. J., Kosian, M. C., Groenewoudt, B. J. & **Jansma, E.** (2015a). Finding a way: Modeling Landscape Prerequisites for Roman and Early-Medieval Routes in the Netherlands. *Geoarchaeology: An international Journal, 30,* 200–222. DOI: https://doi.org/10.1002/gea.21510

Van Lanen, R. J. & **Pierik, H. J.** (2017). *Calculating connectivity patterns in delta landscapes: Modelling Roman and early-medieval route networks and their stability in dynamic lowlands.* Quatenary international.

Van Leusen, P. M., Deeben, J., Hallewas, D., Zoetbrood, P., Kamermans, H. & **Verhagen, J. W. H. P.** (2005). A Baseline for Predictive Modelling in the Netherlands. van Leusen, M. & Kamermans, H. (Eds.), *Predictive Modelling for Archaeological Heritage Management: A Research Agenda. Nederlandse Archeologische Rapporten, 29,* 25–92. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Verhagen, J. W. H. P. (2013). On the Road to Nowhere? Least-Cost Paths, Accessibility and the Predictive Modelling Perspective. *Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, CAA2010,* Contreras, F., Farjas, M. & Melero, F. J. (Eds.), 383–390.

Verhagen, J. W. H. P. & **Whitley, T. G.** (2012). Integrating Archaeological Theory and Predictive Modeling: A Live Report from the Scene. *Journal of Archaeological Method and Theory, 19*(1), 49–100. DOI: https://doi.org/10.1007/s10816-011-9102-7

Vletter, W. (2014). (Semi) automatic extraction from Airborne Laser Scan data of routes and paths in forested areas. *In SPIE proceedings Second International Conference on Remote Sensing and Geoinformation of the Environment, 9229:92291D August 2014.* DOI: https://doi.org/10.1117/12.2069709

Vos, P. C. (2015). *Origin of the Dutch Coastal Landscape* (Distertation thesis, University of Utrecht). Eelde: Barkhuis publishing.

Vos, P. C., Bazelmans, J., Weerts, H. J. T. & **Van der Meulen, H. J. T.** (Eds.), (2011). *Atlas van Nederland in het Holoceen,* Amsterdam.

Vos, P. C. & **De Vries, S.** (2013). *2e generatie paleogeografische kaarten van Nederland (versie 2.0).* Utrecht: Deltares.

White, D. A. & **Barber, S. R.** (2012). Geospatial modeling of pedestrian transportation networks: A case study from precolumbian Oaxaca, Mexico. *Journal of Archaeological Science, 39,* 2684–2696. DOI: https://doi.org/10.1016/j.jas.2012.04.017

Whitley, G. (2005). A brief outline of causality-based cognitive archaeological probabilistic modelling. van Leusen, M. & Kamermans, H. (Eds.), *Predictive Modelling for Archaeological Heritage Management: A Research Agenda,* 123–137. Nederlandse Archeologische Rapporten 29 Amerfoorst: Rijksdienst voor Oudheidkungid Bodemonderzoek.

Wilcox, W. (2009). Archaeological predictive modelling in East Anglia and Norfolk. *In proceedings of Computer Applications to Archaeology 2009 Williamsburg,* Virginia, USA. March 22 26. http://archive.caaconference.org/2009/PapersProceedings.cfm.html.

Yokoyama, R., Shirasawa, M. & **Pike, R.** (2002). Visualizing topography by openness: a new application of image processing to digital elevation models. *Photogrammetric Engineering and Remote Sensing, 68*(3), 257 265.

How to cite this article: Vletter, W. F. and van Lanen, R. J. (2018). Finding Vanished Routes: Applying a Multi-modelling Approach on Lost Route and Path Networks in the Veluwe Region, the Netherlands. *Rural Landscapes: Society, Environment, History*, 5(1): 2, 1–19, DOI: https://doi.org/10.16993/rl.35

Submitted: 03 June 2016 **Accepted:** 10 January 2018 **Published:** 05 February 2018

Rural Landscapes: Society, Environment, History is a peer-reviewed open access journal published by Stockholm University Press.

OPEN ACCESS

Appendix B: Least-cost path (LCP) calculations

In this section we present a more detailed background of the LCP model we have developped for this paper. The flowchart (Fig. B1) shows the workflow applied for generating the LCPs (Section 4.3).

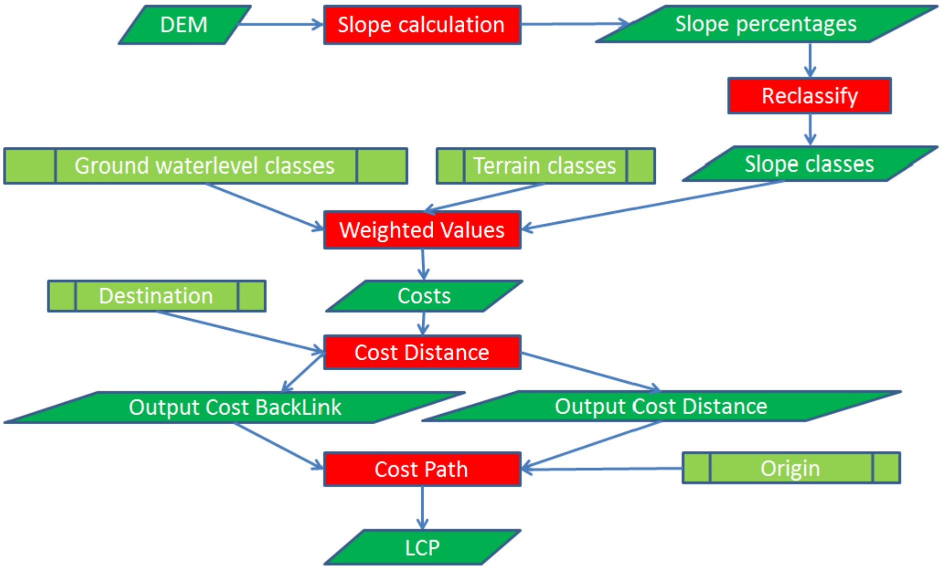


Figure 1: Flowchart of the LCP model

As mentioned before (Section 4.3.), there are three factors influencing the outcome of the model: terrain, slope and groundwater levels. The factors were classified prior to the calculation of the combined friction raster. It is obvious that the allocations of the values to these classes have a crucial impact on the outcome of the model.

Slope values were derived from the digital terrain model (DTM) of the study area as percentage units of measurement. Subsequently, slope percentages were grouped by 'Natural breaks' classification, a statistical method developed to establish the optimal arrangement of values into different classes (Jenks, 1967). Classes representing a group of higher slope percentages were allocated with a higher value (cost) than the one representing lower percentages. Slope percentages higher than 10% were excluded from calculation as the roads of that time probably did not include switchbacks allowing to climb steeper slopes. This number is based on the average of the range of 8% and 12 % threshold in Herzog and Posluschny (2012). In the end in resulted in 10 classes. The class with the highest slope had a cost of 10, the second highest a cost of 9, etc.

The terrain classes needed refining before they were incorporated in the model. Terrain factor is a combination of topographic depressions and lower elevation areas, both of which could represent wetter areas. Depressions were identified with the 'fill' and 'cut fill' tools in ArcGIS. Using the fil tool, depressions based on the DTM were filled to provide a smoother surface. Subsequently,the fillings (i.e. the depressions) were calculated by subtracting the original DTM from the filled DTM. A threshold factor of 6 meters above sea level was employed to distinguish wetter areas from dryer areas and is based on a combination of the soil map, historical 1850 map and the DTM data.

The threshold was chosen by overlaying these sources and determining the height of the boundary between sand and clay areas; the transition zone from the push moraine to the coastal zone was taken into particular account. The raster calculator tool then divided the DTM in areas below and above the threshold factor. The result was combined with the depressions map and produced a terrain map refined into lower and higher areas. The costs of these two classes are based on the terrain coefficients from Soule and Goldman (1972): 1.2 for the higher sandy heath land and 1.8 for lower wetlands.

The groundwater level classes were based on the groundwater-level table of the soil map and needed a small adjustment in ArcGIS. In other words, when a class represents a deep groundwater level a lower value (cost) was allocated. For this purpose the 'reclassify' tool was used.

The groundwater level exist nine classes including subclasses. To make them suitable for the model these has to be regrouped to seven classes, where the lowest groundwater class represents the lowest cost of 1, the second lowest a cost of 2 and so on.

The weighted values define the final costs and a least cost path was calculated with the standard cost distance tools for LCP in ArcGIS between and origin and destination. Naturally, the division of weighted values has an enormous influence on the outcome. The optimal value for each route was achieved by a simple 'trial and error' exercise. This is the most laborious and time consuming part of the model. Nevertheless, this flexibility and the overall flexibility of the model to change values are an asset. Indeed, it is quite easy to investigate a certain factor or make a comparison between factors for a chosen route. Although one should take into account that it is not only the set parameters that define the outcome, but also the software package used (Gietl et al., 2008). The model can be run on a standard desktop computer, which is advantage over other models which require more processing power (Verhagen and Whitley, 2012; White and Barber, 2012).

In order to make a good evaluation of the LCP model, four historical roads were reconstructed: the Hessenweg between Hattem and Voorthuizen, which connected Amsterdam overland to Germany, the road (Harderwijkerweg) between Harderwijk en Arhem and two routes across the Veluwe; from Dieren to Barneveld, and from Apeldoorn to Voorhuizen. These roads have been chosen as they have known historical depth and cross the Veluwe push moraines in different directions and in different routes: from Northeast to Southwest over the brink of the push moraine, from North to South along the western border and from East to West across the central part. For each of these routes different parameter sets were tested. In additon to the 100m route-zone width presented in the main text, we also applied a 200m and 1000m route zone to investigate the four routes further and to make a broader comparison.

Table 1: Correlation per LCP-calculated routes (varying route-zone widths), the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850. When a percentage is in underlined, it indicates that a route performed best in comparison to the others.

Dataset	Route: Arnhem to Harderwijk		
	100m zone	200m zone	1000m zone
ALS-extracted hollow ways	7 %	14%	26%
AD 1600 route network	9%	20%	67%
TMK 1850 routes	58%	72%	88%

Dataset	Route: Hattem to Voorthuizen		
	100m zone	200m zone	1000m zone
ALS-extracted hollow ways	13%	14%	28%
AD 1600 route network	10%	25%	46%
TMK 1850 routes	30%	50%	89%

Dataset	Route: Apeldoorn to Voorthuizen		
	100m zone	200m zone	1000m zone
ALS-extracted hollow ways	9%	13%	39%
AD 1600 route network	21%	30%	50%
TMK 1850 routes	32%	46%	79%

Dataset	Route: Dieren to Barneveld		
	100m zone	200m zone	1000m zone
ALS-extracted hollow ways	1%	1%	1%
AD 1600 route network	3%	7%	47%
TMK 1850 routes	11%	21%	70%

Table 2 provides an overview of correlation percentages per LCP-calculated route. Although the general correlation is highest with the TMK 1850 dataset and the lowest with the ALS-extracted hollow ways, the individual LCP routes show varying results per different route-zone width (buffer). This is not surprising because the 1850 map shows a much higher number of (alternative) roads and paths and the LCP routes we selected were also known to be present in the landscape during that time.

In general we can state that the reconstructed route Arnhem to Harderwijk performed best, followed up by the Hattem to Voorthuizen modelling. However, the modelled Apeldoorn to Voorthuizen route performed best regarding the AD 1600 network. A premature interpretation may suggest that the Apeldoorn Voorthuizen route is older than others, this however is not substantiated by any further evidence and is beyond the limits of these datasets to provide an answer.

Table 2: The weighted values of the factors per route. Where a percentage is underlined, it indicates this factor was most influential for a route.

Routes	*Factors*		
	Slope	***Terrain (low areas)***	***Ground Water level***
Arnhem to Harderwijk	***20%***	***40%***	***40%***
Hattem to Voorthuizen	***5%***	***90%***	***5%***
Apeldoorn to Voorthuizen	***5%***	***90%***	***5%***
Dieren to Barneveld	***33%***	*33%*	***33%***

It is clear that the terrain, representing the low areas, is the most influential factor followed up by the ground water level in this model. However, it is also evident that slope has certain influence in all the routes. The table also demonstrates clearly there is no fixed division of values for routes across the Veluwe. Indeed, it advocates the individual investigation of routes. This may also indicate that the creation of a route network for an area is per definition limited, as individual routes may have their optimal division of factors of influence.

The individual LCP routes are shortly described below.

Route: Harderwijk to Arnhem
If we look at the LCP reconstruction of the Harderwijkerweg, it is clear that in the beginning, from Arnhem, it follows the old Harderwijkerweg better than the more recent route on the TMK 1850 map. These old and new roads come together at a certain point and the modelled route stays reasonably close by. However, after a while there is a divergence, which can be explained by the lower areas class of the terrain factor, which the reconstructed path avoids and the real road runs over it. In the final part the divergence is largest. This may be due to cultural factors, meaning that in the real route a village was included, which led to a small detour.
The overlap with the 1600 network is clearly minor. As mentioned before this is mainly due to lesser density of this network. Increasing the zone improves the overlap. The same accounts for the overlap with ALS extracted roads.

Route: Hattem to Voorthuizen
The LCP itself runs in the beginning between the old and new Hessenweg on the TMK map and then it keeps a certain distance to it and in the final part there is quite a distance between the original route and the path. This has perhaps to do with the fact that the reconstructed path is quite straight and the original makes a little detour to the village of Garderen. This may be due the influence of cultural factors.
Regarding the overlap with the 1600 the overlap is doubled with a zone of 200 meter is used. A further increase results in a relative small improvement. It is the best route lining up with the extracted roads with a 100m zone. However, this picture changes when larger zones are used.

Route: Apeldoorn to Voorthuizen
The third reconstructed road was the one from Apeldoorn to Voorthuizen. This one shows already within itself a lot of variation when confronted with the comparison data sets. Collating to the 1600 map shows that the beginning of the LCP does not come close to a road. In the central part, it is approximately parallel before losing track again in the final part. The comparison with the 1850 shows a different picture. There was generally more overlap. Therefore, the reconstruction for this map was quite good, although still not so good as the one of the Harderwijkerweg.
Regarding the 1600 network, this route performed best for the smallest route zone of 100 meters. This could indicate something over the age of this route. Also this route lines up quite well with the extracted roads when larger route zones are used.

Route: Dieren to Barneveld

The reconstruction of the Dieren Barneveld is the least successful of all least cost paths. Especially at the start the modelled route runs around the Caloumen Berg in a northern route, but the map of 1600 shows a southern turn, while comparison to the 1850 map shows little overlap with a road that could be depicted as regional. In the final part, its performance improves and it follows the corridor between the sand blown areas on the 1850 map quite well. Overlap with hollow ways however, is almost not existent, indicating perhaps that they are less represented in this area, or they have simply vanished over time.

Additional reference

Jenks, G. 1967. The Data Model Concept in Statistical Mapping. *International Yearbook of Cartography* 7, 186–190.

Chapter 9 First steps for the use of a gaming engine for historical road and path research.

This article has been published in the peer reviewed Journal of Computer Applications in Archaeology on 28 February 2019. The PhD student is the only author and thus the whole text is written by him. The article focuses on the possible use of gaming engines for (re-)modelling historical routes.

journal of computer applications in archaeology

Vletter, W. 2019. First Steps in the Use of a Game Engine for Historical Roads and Paths Research. *Journal of Computer Applications in Archaeology,* 2(1), pp. 3–11. DOI: https://doi.org/10.5334/jcaa.18

CASE STUDY

First Steps in the Use of a Game Engine for Historical Roads and Paths Research

Willem Vletter

Game engines are developing fast and are used in several scientific disciplines. In the domain of cultural heritage, they have been applied mostly for dynamic visualization. On the other hand, GISs are employed to address research questions with a spatial component. In an ideal situation, the visualization power and analytical strength of the two technologies should be combined in one system. With this in mind, the analytical potential of a game engine was investigated based on a comparison with GIS analysis of historical routes. The outcome demonstrates the suitability of the game engine in offering extra analytical possibilities. This analytical capacity encourages further script developments in building more historically accurate models.

Keywords: gaming engine; roads; history; GIS; LCP

Introduction

Geographic Information Systems (GIS) are widely used in research for the visualization and spatial analysis of historical data. Their power lies in the fact that they are able to combine and visualize diverse datasets containing geographical information. Archaeological research questions, for example, can be investigated by combining landscape models with historical data and applying Least Cost Path (LCP) analysis to reconstruct historical routes and identify potential corridors for unknown routes (Citter 2012; Doneus 2013; Herzog & Posluschny 2012; Van Lanen et al. 2015; Verhagen 2013).

The use of gaming engines in archaeology is not new (Anderson et al. 2010). In the gaming world pathfinding is often used and discussed (Buro 2004; Hagelbäck & Johansson 2008; Matthews 2002; Orkin 2002 & 2004; Stout 2000) However, gaming engines for investigation of movement in the past are very little applied (Anderson et al. 2010; Ch'ng 2007). Moreover, comparisons based on pathfinding (route modeling) between gaming engines and GIS were not found. Nevertheless, gaming engines are interesting from the perspective of movement research.

The term "believable" in games is often used in the context of movement (Anderson et al. 2010; Ch'ng 2009; Jurney 2008; Nareyek 2004; Olsson 2008). For example, it is not considered *believable* for humans to walk through walls nor across water. Therefore, the movement of an agent should be constrained by believable physical barriers such as a wall or body of water. Believable movement in games has similarities with realistic movement within GIS where constraints can be modelled and thus, behavior approaches, rational decision-making or artificial intelligence. In this sense, the scientific spatial analysis of movement within GIS and the movement of agents in a game environment share a common interest.

Game engine features are currently advancing within a growing market. It is interesting, therefore, to consider whether results from a game engine are comparable to commonly used GIS calculations. For the purpose of this paper, the game engine *Unity* is used. Its capabilities include: excellent rendering, ease of use, multi-player options and expandability through custom scripting. Unity also boasts a large support community for development (Ch'ng 2007).

The full range of Unity's capabilities is not explored here as the specific purpose of this analysis is to investigate the potential in historical road and path research. Within this scope, a comparison will be made between the LCP results in ArcGIS and Unity. Datasets derived from previous research into historical routes of the Leitha Hills in Austria (Doneus & Briese 2011) are used for this comparison.

Case Study Area

The Leitha Hills are forested, middle-range mountains lying about 40 km southeast from Vienna covering an area of *c.*25 km^2 (**Figure 1**). Many roads and paths are present here, which may date from prehistoric times. Certain routes are dated to the Middle Ages and make the area interesting for investigation. The availability of high-resolution relief data for the area further enhances the suitability of the Leitha Hills for historical route research (**Table 1**). This dataset will be discussed in detail below.

Methods and Workflow

A comparison between GIS (ArcGIS software) and a game engine is the central theme of this paper.

Vienna Institute for Archaeological Science, AT
willem.vletter@univie.ac.at

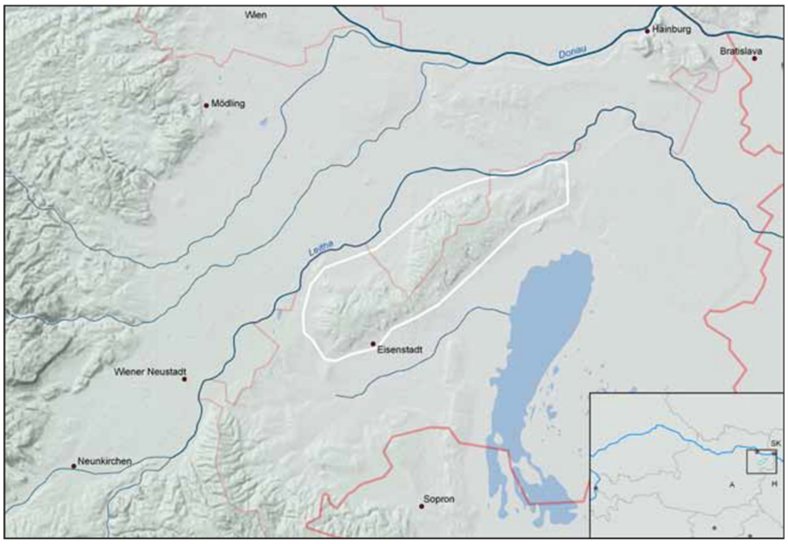


Figure 1: The Leitha Hills outlined in white (Doneus & Briese 2011).

Table 1: The meta-information of the ALS data used in this paper (Doneus & Briese, 2011).

ALS project	Leitha Hills
Purpose of scan	Archaeology
Time of Data Acquisition	March-12th of April 2007
Point distribution (pt. per sq.m)	7
Scanner Type	Riegle LMS-Q680i Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	36 m/s
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Robust interpolation (SCOP^{++})
DTM-Resolution	0.5 m

A game engine is a platform where computer games are developed with integrated tools or alternatively, by writing additional computer scripts.

LCP modelling provided the analytical basis for the comparison between ArcGIS and Unity. LCP analysis calculates a path between two points, which represents the lowest cost in movement (Howey, 2011). The corresponding cost function should be built on variety of factors which influence travel, like personal preference, administrative borders, religious incentives, social customs, existing sites and terrain circumstances. However, quantifying all these factors is often complicated. Indeed, terrain circumstances are probably the easiest to incorporate. Slope factor in particular is almost always used as it is easily applied and has often been the sole factor in LCP calculations (Herzog & Posluschny, 2011). However, the use of slope as a sole input is criticized for making the models too dependent on topography (Wheatly & Gillings, 2002). Nevertheless, they are two good reasons to start only with slope. First, it is difficult to incorporate other factors, especially if they have to function equally in both GIS and a gaming engine. Second, it is good modelling practice to begin with a simple model. Once the model works, other factors can be added. The Dijkstra algorithm is used in both applications for the LCP analysis (Anderson et al. 2010; Herzog 2014; Nareyek 2004). This is important as research has proven that different algorithms can deliver different results in LCP modelling, even with the same datasets and parameters (Gietl et al. 2007; Herzog 2013). The Dijkstra algorithm calculates the lowest cost on the basis of a cost surface and the backwards calculation of the lowest cost from destination to end points (Herzog 2014). A cost surface represents cost values based on the cost function of all the pixels in a digital terrain model (DTM) (Crutchley 2010; Opitz & Cowley 2012).

The relief or digital terrain model (DTM) for the analysis is derived from an Airborne Laser Scan (ALS) dataset of the study area. The most important parameters of the collection of the ALS data are listed the table below.

Both Unity and ArcGIS make use of the same DTM to calculate the LCP. In ArcGIS, the import of the DTM is straightforward. In Unity extra steps are necessary to import the DTM in a format that allows LCP modelling.

The initial step in ArcGIS involves amalgamating all the terrain tiles into a continuous surface. The model is then rotated as the Unity grid has an origin point in the top left corner, whereas the grid origin point of the ArcGIS data is the bottom left corner. The next step is to convert the tiff format file into a raw format file necessary for terrains in Unity, by using a simple line command in GDAL. The latter is software which enhances raster data. By the same command, the original tiff file is rescaled and changed into the 16-bit type necessary to complete the import preparation of the DTM into Unity.

A shape file of roads and paths extracted from previous research (Vletter 2014) can also be imported. It is crucial that the roads and paths align with the terrain very closely to enhance the analytical purposes. The complexity lies in the fact that a shape file is 2D and the terrain model in Unity is 3D. This means that the shape file should be draped over the terrain model. This problem is resolved by converting shape file into raster format.

However, importing the complete DTM and the whole extracted route network in one step results in a loss of detail. This issue is caused by the maximum pixel size allowed for images in Unity. At the moment of writing, the limit is 4096 × 4096 pixels. It renders the DTM with little detail and extracted roads blurry when zoomed in. It was decided therefore, to repeat the steps for a smaller tile of 1 km^2.

As can been seen in **Figure 2** below, the roads and paths align fairly well with the height model and are sufficiently visible. This means that to maintain high resolution during import, the original DTM must be split up in smaller tiles; similar applies to the import of the extracted routes files.

The Reconstruction Possibilities in Unity

In order to reconstruct the historical road and path networks in a gaming engine like Unity, the following minimum components are needed: physical landscape, roads and paths, aspects of time, vegetation and players (agents) in the landscape. The topography and extracted roads are already mentioned above, while the possibilities for incorporating the influence of surface, time, vegetation and players (agents) are discussed below.

Terrain Characteristics

The cost of movement varies for different terrains and terrain covers (Herzog 2013). Additionally, the surface itself influences the energy cost (Caspersen et al. 1985; Soule & Goldman, 1972). These varieties in energy cost can be reflected in Unity by using different layers, whereby each layer represents a certain soil and its relative cost (factor) in comparison with other soils. This determines the speed for the movement of an agent and enables comparison.

Vegetation

No trees were implemented in the model for two main reasons. First, there is insufficient information about the historical development of vegetation of the Leitha area to recreate it in Unity. Second, the transport mode chosen influences the level of obstructions such as trees. For example, trees do not seem to be real obstacles for pack animals nor humans following small paths, as can they easily go around them. Navigation of a wooded area though, is more complex for wheeled transport, especially a horse-drawn wagon. Consequently, the influence of vegetation was set aside as the predominant mode of transport is uncertain.

Time

The use and the conditions of road and path networks can change over time. Time plays a role for roads and paths on two levels. First, there is 'seasonal time', in other words the influence of the seasons on the use of the roads and paths. Second, there are periods of time, thus speaking of periods covering decades, or even centuries. Over longer

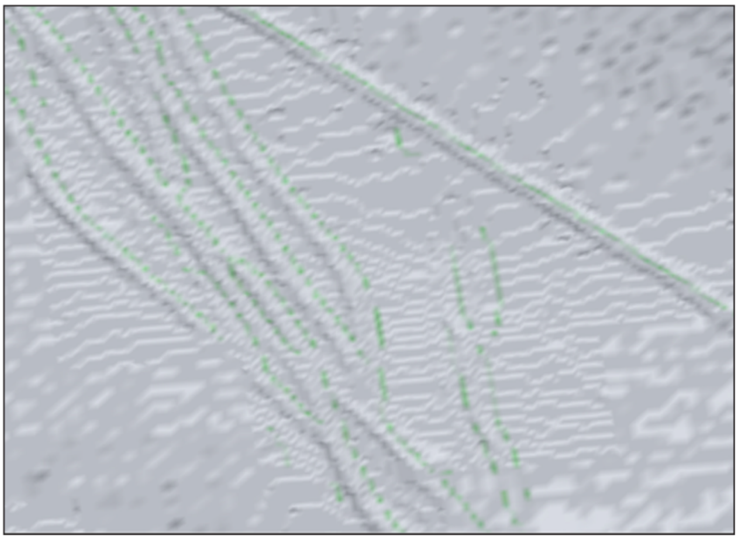


Figure 2: Imported as a texture file, the extracted roads and paths line up well with the Leitha Hills height model in Unity.

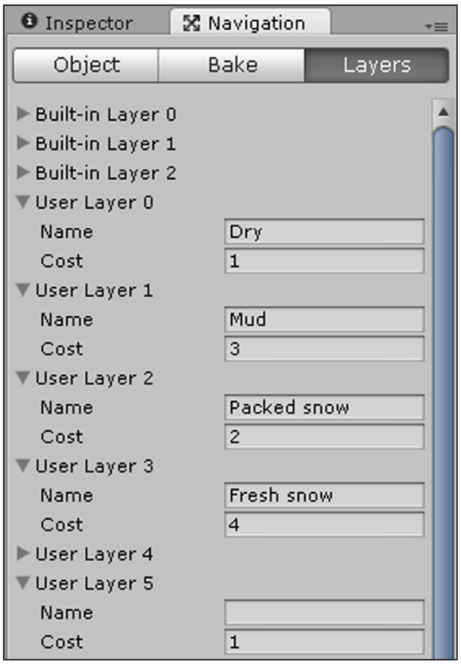
periods of time, road networks can disappear and be replaced by others due to political, economic or natural reasons. The dynamics of roads is often underestimated (Fovet & Zaksek 2014).

In order to visualize the road and path networks from separate periods, a 'slider' function can be applied in both Unity and GIS (**Figure 3**). By moving the slider to a given period, an imported shape file of roads and paths pertaining to that same period can be visualized. This function allows development of route networks to be analyzed the chronologically. The periods linked to the slider depend on the available data. For more recent periods, historical maps are primary source material. For earlier periods, topography and interpretation of the known archaeological record are most important. The result though makes the earlier reconstructed networks less reliable.

Agents

The final components for the analysis are the players or agents. In order to reconstruct/model them, some knowledge of how and when people went into the hills is necessary. Historically, the Leitha Hills have attracted human activity for many reasons, including economic (quarry, forestry, viticulture and stock breeding), religious and travel (Krizsanits & Horvath 2012). We can translate these motives into possible characters or transport modes.

For forestry, it is probable that a two-wheeled cart was used. Such a cart is considered most suitable for transportation in the forest because of flexibility of movement compared to a four-wheeled wagon. Medieval paintings with two-wheeled carts from other middle-mountain areas in Europe support this theory (Tarr 1978).



▶ Built-in Layer 0
▶ Built-in Layer 1
▶ Built-in Layer 2
▼ User Layer 0
Name Dry
Cost 1
▼ User Layer 1
Name Mud
Cost 3
▼ User Layer 2
Name Packed snow
Cost 2
▼ User Layer 3
Name Fresh snow
Cost 4
▶ User Layer 4
▼ User Layer 5
Name
Cost 1

Figure 3: The relative costs of different surfaces.

Pack animals such as mules or horses are an even more flexible transportation mode than the two-wheeled cart. Cows, also good climbers, were traditionally pastured on the Leitha Hills. Pasturing was part of a cattle trading route stretching from the Hungarian plane to Vienna (Krizsanits & Horvath, 2012). We have also people who went on foot up into the Leitha Hills for a multitude of reasons; religion, smuggling, travel, hunting, or for leisure. Finally, although the horse-drawn four-wheeled car was a transport mode which was intentionally not taken in consideration here, historical photographs from around 1900 demonstrate that it was used for quarrying. However, the quarries of the 19th and 20th century were mostly located on edge of the Leitha Hills area and linked with good roads to major centres, such as Vienna. Two-wheeled carts were most probably used for quarries located deeper in the forest.

Analytical Possibilities in Unity

The primary concern of this study is to investigate is the analytical potential of Unity. In this section, LCP analysis utilizing integrated tools within Unity as well as LCP analysis based on the scripting will be tested and compared to similar results produced within ArcGIS. However, before proceeding, it is necessary to test first the validity of LCP analysis for roads and paths in the Leitha Hills.

Validation of LCP in ArcGIS

The validity for LCP modelling was tested in ArcGIS. In other words, how well do the results of LCP modelling approximate known historical roads and paths? Previously, LCP and variations of this technique have been tested for the Leitha Hills using ArcGIS 9.3 and a 10 m raster DTM (Doneus 2013). The most important outcome of that study was how a combination of 'openness' analysis and slope analysis delivered excellent results within the Leitha Hills area.

Ideally, for the purpose of the present study, openness analysis should also be applied within Unity. However, a problem was caused by the known smoothing of the terrain in Unity. This smoothing would influence the outcome of an openness analysis and thus reduce the objectivity of the comparison with ArcGIS. Therefore, it was decided to investigate with only one variable in the first instance: the influence of the terrain within Unity and ArcGIS. The validity was checked by a LCP model based on slope raster calculation in ArcGIS 10.3.

For consistency to the above mentioned case study, a 10m raster was used. However, this resulted in unrealistic routes including enormous detours over virtually flat areas and unnecessary crossings of streams. After some trial and error, a 0.5 m raster delivered the best results and was used in all subsequent calculations. In order to make the analysis more realistic and provide a possible time depth, a path was modelled between two caves, both of which had known long use in the past.

The results were encouraging. About 87% of the path lined up with, or was parallel (within a 50 m range) to, documented roads and paths (**Figure 5**). The reverse exercise had the same result. However, close examination of the outcome resulted in two observations. First, examination of the topography showed that the calculated path to be logical and almost the only feasible solution. Second, the path partly follows modern roads, which caused some suspicion.

Subsequently, a second test was done in another part of the Leitha Hills between caves of which the historical usage is unknown (**Figure 6**). The results of the LCP modelling were also encouraging. About 78% of the modeled route lines up with, or are parallel (within 50 m) to roads and paths visible on the ALS data. For this reason, it was assumed that LCP modelling based solely on slope was a sufficiently valid tool for determining roads and paths in the Leitha Hills.

For comparison to the analysis within Unity, a smaller area (tile) of one square kilometer was considered due to the limitations of the maximum image size resolution of the game engine. In ArcGIS, three points were created and the least cost path between these three points was calculated (**Figure 7**). The same exercise was done within Unity.

LCP Navigation Tool

Movement within Unity is based essentially on the 'navigation' tool. This tool is set up to let an agent move around in a game environment. The standard parameters set for this tool were worthy of further investigation.

Slope or inclination is an important parameter. Overcoming the slope gradient was of importance for all the transportation modes. For modes of wheeled transport, this was especially true. According to other studies, between 8% and 12% was the maximum inclination range a cart or wagon could overcome (Herzog & Posluschny 2011). The load, of course, played a contributing factor. It is important to insert a slope threshold when navigating within Unity; the navigation tool permits the setting of a maximum slope which can be traversed.

The width of roads is another parameter, which is also of importance for wheeled vehicles. Establishing a suitable road/path width though, is difficult as there was not only a huge variation in the size of cars and carts over time, but also within a certain time periods (Denecke 1969). This variation and uncertainty surrounding cart widths makes setting a limiting factor (i.e. the narrowest path one can pass through) difficult. Moreover, setting a radius similar to that of a probable cart width, limited the processing capability of Unity and the parameter was unused.

As mentioned above, different relative costs can be set by creating different layers which can be applied (**Figure 4**). Once all the parameters have been set, a Navigation Mesh (NavMesh) that shows the areas where the agent can move can be generated. Unfortunately, the outcome of the NavMesh baking did not produce the desired outcome. (See **Figure 9**).

From **Figure 8**, it is clear that artificial terraces are created using NavMesh. These processing artefacts hinder the pathfinding within the navigation tool as they form unnatural obstacles. Adjusting the analysis parameters to make the terrain flatter risked creating an equally unrealistic landscape. This limitation is possibly the result of a too-low resolution of the DTM or alternatively, the

Tag Untagged Layer Default

Position X -191.3754 Y -3524.88 Z 1875.463
Rotation X 0 Y 0 Z 0
Scale X 1 Y 1 Z 1

☑ Sliders (Script)
Script Sliders
HSlider Value 0

Figure 4: The slider function in ArcGIS/Unity.

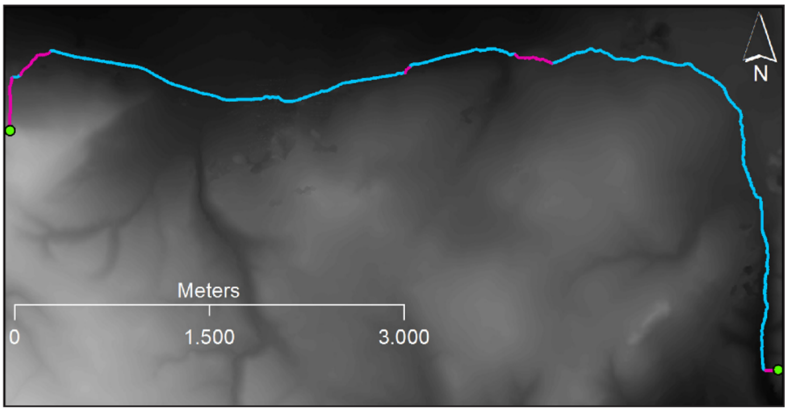


Figure 5: The location of the two caves (in green). The LCP path (in blue) and the sections that didn't align (in purple) to roads and paths visible on the ALS data.

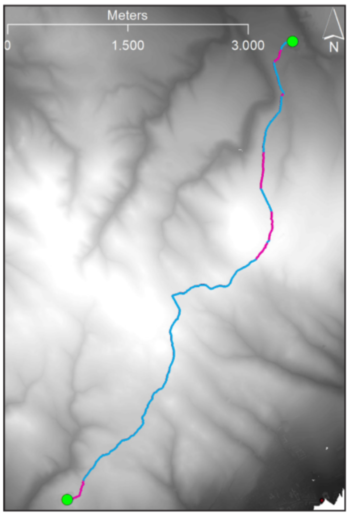


Figure 6: The location of the two caves (in green); the LCP path (in blue) and the parts that didn't align (in purple) to roads and paths visible on the ALS data.

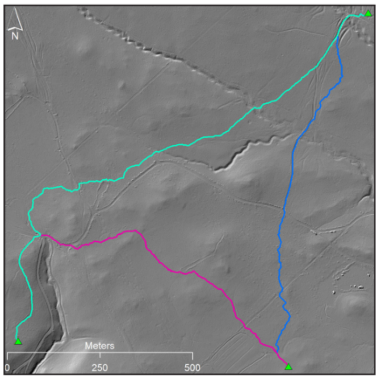


Figure 7: The results of LCP analysis in ArcGIS between points of the selected tile of 1 km². The final part of paths with different starting points and the same destination overlap. This can be explained by the distribution of the points in the corners of the square kilometer.

unsuitability of the navigation tool. Both possibilities may be related to the maximum image size resolution (2048 × 2048) allowed within Unity. Unfortunately, this issue remains unresolved at the time of writing.

LCP Scripting

Besides the navigation tool, scripting provides another possibility to move around a gaming environment using languages like Java (adapted for Unity), C# and Booh. Indeed, the power of a game engine like Unity is that user can create a lot of features by scripting. For this research, a script has been used that comes from the A* Pathfinding Project of Aron Granberg (Granberg 2018), a free-to-use script written in C# for Unity. One interesting feature of this tool is that multi-agents can be created. A* can also be combined with the standard navigation tool of NavMesh, described earlier. However, the grid option was chosen for modelling movement as the NavMesh did not function well and made computation too heavy. This means that the agent walks over a grid. Parameters are set within A* pathfinding script and defines where the agent actually can go.

Several tests were carried out in order to find 'realistic' settings, meaning movement parameters which approximate human movement. The lowest climb (vertical) height was 30cm and the inclination was 20% to allow the agent reach its destination. Below these thresholds, the agent either does not reach its destination or an error message related to processing capacity is triggered. To summarize, these settings come close to realistic movement for a human being or a draught animal. For movement of cart and wagons the 20% inclination is probably too high.

In the following steps, routes were computed between the same three points used above in ArcGIS. The comparison demonstrated that in general, Unity delivers comparable results to ArcGIS. Both applications avoid the main obstacles in a similar way. However, the results between the two don't align, with the Unity results seeming unrealistically too straight. The fact their results diverge doesn't constitute a real problem as different software packages can result in different results using the same data and parameters for creating a least cost path model (Gietl et al. 2008). Their sensitivity to minor obstacles, meaning micro relief differences, is a major point of difference between the two applications. The outcome in ArcGIS seems to be too sensitive to these obstacles as

Figure 8: The NavMesh outcome: the navigable areas (in purple).

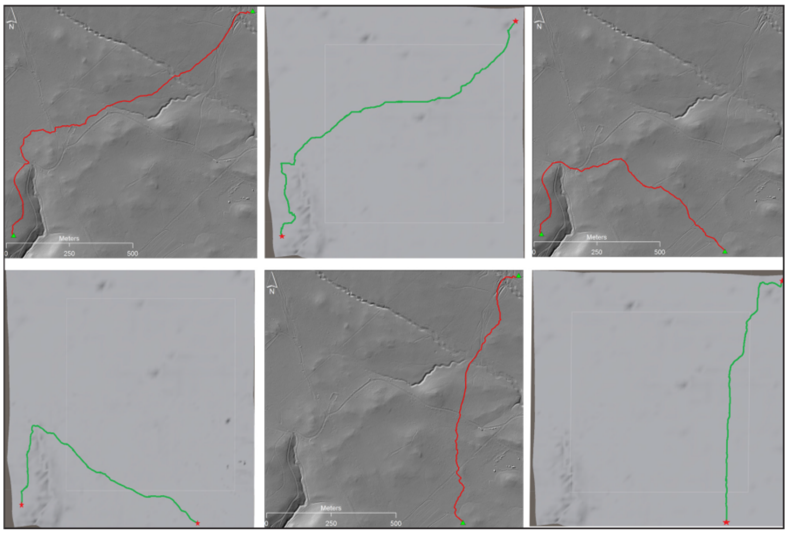


Figure 9: Comparison of LCP results between ArcGIS (left) and Unity (right) on area of 1 km². Due to resolution differences, the DTM in ArcGIS is much clearer. Furthermore, it shows that in both applications the stream in the lower left is clearly avoided. In the central part of both tests the results show the largest differences in routing. Additionally, the routes in ArcGIS are more winding than the ones in Unity which tends to produce long straight sections.

a relatively high number of small turns are made over short distances, which does not appear realistic. Unity, on the other hand, shows a 'lack' of sensitivity, choosing a very straight path which ignores minor obstacles. This is probably due to the smoothing in Unity, which is also visible in **Figure 9**. It means that for analysis in ArcGIS, a lower resolution on a small scale or, alternatively, changing the analysis parameters, would possibly work better. However, worse results in ArcGIS were obtained when a lower resolution was used in the path modelling for larger areas (see section 5.1). In Unity, a higher sensitivity must be created either through a higher resolution or by changing the settings of DTM.

Discussion

There are clearly disadvantages in the use a game engine. The principal one is that computational power is needed (Nareyek 2004). Increasing the processing complexity leads to a rise of computational power. Insufficient processing power will slow down the game or even make the game crash. The level of detail of large areas (such as a study area DTM) is also limited due to the large computational power needed. Further scripting skills are needed to bring the analytical strength of gaming engine to a higher level (Nareyek 2004). However, these issues can be resolved through the continued evolution of scripting languages as well as the development of computing power of PCs.

There are also several advantages in using a game engine. First, the landscape can be made more realistic, which enlarges the embodiment and perception of the land under investigation (Ch'ng 2007 & 2010). The movement of the player can be shown from the agent position, like a video, instead of the 2-D outcome of logarithm in GIS. Incorporating multi-players which can interact with one another is also possible. An experimental study could be carried out by 'walking' in the reconstructed landscape with a non-predefined agent (Ch'ng 2009). This also adheres to the embodiment of the landscape. Additionally, areas to be avoided can be created by making use of influence maps (Paanakker 2008), which could in turn simulate border areas (Casimir & Roa 1992).

Conclusion

Resolution issues are a possible limitation if large DTMs or extracted roads and paths are imported. Such issues can be solved by splitting up the DTM or the roads and paths file into smaller tiles and reassembled in Unity. The resolution of the 1 sq. km tile presented in this study produced good results, while the roads and paths texture lined up encouragingly well with the height model. A slider function created a temporal-spatial model by visualizing the road and path networks through different periods.

The use of the navigation tool of Unity was, instead, disappointing. The NavMesh baking did not result in walk-able areas which could be used for analytical purpose. This may be due to either a resolution issue or to a limited capacity of the navigation tool. This issue has yet to be resolved before spatial modelling can take place with this tool.

In comparison, the script of the A* pathfinding project worked well on the imported DTM. The comparison of results to the GIS analysis results showed that Unity delivers similar results, despite not aligning exactly. This outcome, together with the advantages of the fast developing gaming world, make that the application of game engines for route modelling look promising and hopefully future research will live up to these expectations.

Acknowledgements

I would like to thank Eamonn Baldwin of University of Birmingham, Eugene Ch'ng of the University of Nottingham Ningbo in China and James Wesolowski of the University of Arkansas for putting me on the right track. Also special thanks go to Herman Veluwekamp, PhD researcher at the faculty of Philosophy at the University of Groningen, for his help with GDAL software.

Competing Interests

The author has no competing interests to declare.

References

Anderson, EF, McLoughlin, L, Liarokapis, F, Peters, Petridis, P and **de Freitas, S.** 2010. Developing serious games for cultural heritage: A state-of-the-art review. *Virtual Reality*, 14: 255–275. DOI: https://doi.org/10.1007/s10055-010-0177-3

Buro, M. 2004. Call for AI research in RTS games. In: Ferguson, G and McGuinness, D (eds.), *The AAAI-04 Workshop on Challenges in Game AI*, 139–142. Menlo Park: The AAAI Pres.

Casimir, M and **Rao, A.** (eds.) 1992. *Mobility and Territoriality. Social and Spatial Boundaries among Foragers, Fishers, Pastoralists and Peripatetics*. Oxford: Berg.

Caspersen, CJ, Powell, KE and **Christenson, GM.** 1985. Physical activity, exercise, and physical fitness: Definitions and distinctions for health-related research. *Public Health Reports*, 100(2): 126–131.

Ch'ng, E. 2007. Using Games Engines for Archaeological Visualization: Recreating Lost Worlds. In: Mehdi, Q, Estraillier, P and Eboueya, M (eds.), *AI, Animation, Mobile, Educational and Serious Games. Proceedings of the 11th International Conference on Computer Games*, 26–30. Wolverhampton: The university of Wolverhampton School of Computing and information technology.

Ch'ng, E. 2009. Experiential archaeology: Is virtual time travel possible? *Journal of Cultural Heritage*, 10: 458–470. DOI: https://doi.org/10.1016/j.culher.2009.02.001

Citter, C. 2012. Modelli predittivi e archeologia postclassica: vecchi strumenti e nuove prospettive. In: Redi, F and Forgione. A (eds.), *Atti del VI convegno nazionale della SAMI, L'Aquila, 2012*, 3–6. *Modelli predittivi e archeologia postclassica: vecchi strumenti e nuove prospettive*, 12–15. Firenze: Edizioni All'Insegna del Giglio.

Crutchley, S. 2010. *The Light Fantastic, using airborne lidar in archaeological survey*. Swindon: English Heritage.

Denecke, D. 1969. *Methodische Untersuchungen zur historisch geographischen Wegeforschung im Raum zwischen Solling und Harz. Ein Beitr. zur Rekonstruktion d. mittelalterl. Kulturlandschaft*. Göttingen: Goltze.

Doneus, M. 2013. Die hinterlassene Landschaft Prospektion und Interpretation. *Die Landschaftsarchäologie in Mitteilungen der Prähistorischen Kommission*, 78. Vienna: OAW. DOI: https://doi.org/10.2307/j.ctt1vw0qcb

Doneus, M and **Briese, C.** 2011. Airborne Laser Scanning in Forested Areas – Potential and Limitations of an Archaeological Prospection Technique. In: Cowley, D (ed.). *Remote Sensing for Archaeological Heritage Management. Proceedings EAC*, 53–76. Budapest: Archaeolingua.

Fovet, E and **Zaksek, K.** 2014. Path network modelling and network of aggregated settlements: a case study in Languedoc (Southeastern France). In: Polla, S and Verhagen, Ph (eds.), *Computational approaches to the study of movement in archaeology. Theory, practice and interpretation of factors and effects of long term landscape formation and transformation*, 43–72. Berlin: de Gruyter.

Gietl, R, Doneus, M and **Fera, M.** 2008. Cost Distance Analysis in an Alpine Environment: Comparison of Different Cost Surface Modules. In: Posluschny, A, Lambers, K and Herzog, I (eds.), *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology Berlin, Germany, April 2–6, 2007 (Kolloquien zur Vor- und Frühgeschichte)*, 10: 336–341. Bonn: Dr Rudolf Habelt GmbH.

Granberg, A. 2018. *A*Pathfinding Project*. Available at: https://arongranberg.com/astar/ [Last accessed 31 December 2018].

Hagelbäck, J and **Johansson, SJ.** 2008. The rise of potential fields in real time strategy bots. In: Darken, C and Mateas. M (eds.), *AIIDE 08: The Fourth Artificial Intelligence and Interactive Digital Entertainment Conference*, 42–47. Menlo Park: The AAAI Pres.

Herzog, I. 2013. Theory and practice of cost functions. In: Contreras, MF and Melero. FJ (eds.), *Fusion of culture. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*, 375–382. Oxford: Archaeopress.

Herzog, I. 2014. Least-cost Paths. Some Methodological Issues. *Internet Archaeology*, 36. [Last accessed 28 May 2014]. DOI: https://doi.org/10.11141/ia.36.5

Herzog, I and **Posluschny, A.** 2011. Tilt – Slope-Dependent Least Cost Path Calculations Revisited. In: Jerem, EE, Redő, F and Szeverényi, V (eds.). *On the Road to Reconstructing the Past. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 36th International Conference. Budapest, April 2–6, 2008*, 212–218. Budapest: Archaeolingua.

Howey, MCL. 2011. Multiple pathways across past landscapes: Circuit theory as a complementary geospatial method to least cost path for modeling past movement. *Journal of Archaeological Science*, 38: 2523–2535. DOI: https://doi.org/10.1016/j.jas.2011.03.024

Jurney, C. 2008. Company of Heroes Squad Formations Explained. *AI game programming wisdom. Cengage Learning PTR*, 4: 61–69.

Krizsanits, B and **Horvath, M.** 2012. *Das Leithagebirge. Grenze und Verbindung*. Weitra: Bibliothek der Provinz.

Chapter 10 General Discussion

10. 1 – Introduction

In order to discuss the outcomes of the dissertation, each step of the methodology will be dealt with. This will be done in the following way. For each methodological step, the results, issues, related literature and future research will be spoken of. The results and issues are closely linked and therefore gathered in subchapters. The related literature and future research form separate subchapters. The issues and results subchapters deal with the results, limitations of the research, unexpected problems, data quality, and similar topics. In the related literature segment. other research with the same or similar objectives or techniques will be confronted. The related literature segment is of importance because since the beginning of this dissertation, ten years ago, several developments have taken place in the research field. When beneficial a link is made with the results and issues of the methodological steps of this dissertation. The future research subchapters give way to the ideas in which the specific methodological step can be further developed or developments in the research field. In the final subchapters, an answer will be given to the sub research questions and the contribution to the archaeological field will be discussed.

10. 2 – Extraction and Mapping of Roads

10.2.1 Results and issues of the extraction step of the methodology step.

The visualisation of roads and paths is crucial for the extraction. The openness technique combined with the Feature Analyst model, explained in chapter two, proved best. Indeed, the extraction model based on ALS data of the Leitha Hills resulted in quite good results. The same model applied to the Veluwe led to much more noise and unwanted extracted features. Adjustment of the model to the Veluwe situation led to improvements. However, the results for the Veluwe were clearly less satisfactory. Differences in landscape and its use influence the discrepancy of quality of the results between the two research areas.

Three main differences can be distinguished. First of all, the topographic height differences in the Veluwe are clearly less evident than in the Leitha Hills. In other words, the Veluwe area is much flatter that the Leitha Hills. Secondly, the soil is different in the Veluwe. In the Leitha Hills the soils are mostly made of chalk. In the Veluwe this is sand. This means that the erosion level in the Veluwe is higher especially in the past, when huge zones suffered from sand drifts. These have as a consequence that the traces of historical routes and paths are subtle and often eroded or covered by sand blows. Thirdly the Veluwe area has been crossed and used much more than the Leitha hills, especially in the 19th and 20th century, leading to several kinds of linear features with little historical depth.

Concluding, for the Leitha hills the combination of visualisation with openness and the extraction with Feature Analyst worked quite well. For the Veluwe area the situation was more complicated because of the smaller height differences, the higher number of linear features and the sandy soils. This made the extraction more complicated and less successful. Indeed, some extra elaborations were needed. Nevertheless, the extraction also in the Veluwe delivered a time gain and a data set which could be used in the following step of the methodology.

10.2.2 Comparison with other extraction methods.

The technical development for extraction and visualisation is going on continuously. Indeed, a lot of new developments are taking place. Here below some of the most important articles will be discussed. When needed a relation is made between the visualisation and extraction applied in this dissertation.

Kokalj and Somrak (2019) wrote a paper about improving the visibility of features by blending different visualisation techniques. The blending is based on stacking imagery. The opacity, thus translucency, of the above layer(s) permits how much detail of the layer(s) is visualised in final top stack. In their attempt, they use openness next to slope and sky view factor, as one of the layers which is suited for subtle features as the concavity of pathways. Interesting is the application of linear stretch in histogram of openness imagery to improve visibility. Clipping the lower and higher values parts improved their results, as did setting the search range to 5-10 meters, leaving out the first 4 meters. This could also well be feasible for both the Veluwe and the Leitha hills area. For the latter area the High Dynamic Range has been changed in Photo Shop to improve the visualisation (see chapter 2). However, the results of effort were such that it did not significantly improve the visuality of the features, so it was left out. For the Veluwe, because of the flatness of the landscape the benefits of the visualisation method of Kokalj and Somrak may be higher. Additionally, Herzog (2013) argues that sunken roads are best found by local relief model or openness. Doneus (2013) had already found for the Leitha Hills that openness was the best option. For this reason openness was applied both for the Leitha Hills and the Veluwe. In both study areas, openness proved indeed good results.

Regarding the detection, Sevara et al. (2016) made a double comparison as they have investigated both pixel based and object-based image analysis (OBIA) detection in two different study areas. Both detection techniques appeared beneficial in both study areas. However, the object-based detection with mainly one type of archaeological object performed clearly best, mainly due to the use of fuzzy logic in the OBIA. Further it is easier to develop a model or workflow for one targeted research object than for multiple objects. By extension, results in a more complex landscape are less than in a more uniform landscape. Therefore, a focus on linear objects like pathways is a good strategy, especially in complex landscapes. The research shows also, with a few exceptions of deep hollow roads, that OBIA performs better for linear concave features like roads. The authors suggest that template matching, creating a training set, in combination with targeted detection for image analysis of objects with small differences with environment. In another words, it seems suited for roads when there are subtle differences in topography. Template matching has been carried out in the extraction model for the Leitha hills and the Veluwe. The conclusions of Sevara et al. line up with the findings of Blaschke & Strobl (2001) who conclude that segment-based classification techniques in most of the cases outperforms pixel-based segmentation. Similarly, Davis (2019) deals with OBIA, which is a form of machine learning. He also concludes that OBIA based approaches are more effective than pixel based. OBIA use multiple variables like pixel value, neighbourhood analysis, object shape, textural information and geographic context. Further, he stresses the importance of expert knowledge (manual control) and control in the field.

OBIA is considered well suited for detecting and extracting of pathways as they are small, structural, homogenous, and differ in local topography. However, a fundamental condition for the success of OBIA is that high quality data is needed. Indeed, if the resolution is not sufficient, a high number of false negatives and false positives appear. Furthermore, in topographic information, augmenting the number of viables and using multiscalar applications, the performance of OBIA improves. Davis argues that template matching has the disadvantage of a lot of false positives and negatives. Critique on the work of this dissertation is that this kind of misclassification rates are not given and that was only noted that 80 % of the linear segments extracted were indeed roads or paths (Herzog 2017). Further it was not clear that this number accounted for the whole area of the Leitha Hills and not just a number of small cases. Nevertheless, automatic extraction of historical roads and paths needs further research. The e-cognition software, as mentioned earlier, seems to have more possibilities when good training sets are available.

Davis further advocates a comparison of extraction methods, such as that used in the extraction step of the methodology. He acknowledges the difficulty of sometimes applying extraction models from one region to another, which was experienced applying the Leitha hills model to the Veluwe. Nevertheless, the created training set for the Leitha hills could be applied to middle mountain regions. The same applies for the one of the Veluwe for quite flat sandy areas.

Turning to OBIA, there are several interesting papers. For instance, an example of successful, though not perfect, application of OBIA for mounds is presented by Davies Sanger & Lipo (2019). Interesting in this article is the use of red-relief image map (RRIM) to visualize feature. RRIM combines negative and positive openness with slope, in which the colour red is used to show the inclination of the slope. Gallwey et al. (2021) also shows a quite successful application of machine learning for detecting mines on ALS visualisations, making use of a lunar training dataset and hereby bypassing the lack of available training sets for archaeological purposes. Moreover, this model it is said to be applicable to other mining areas as it can be applied to ALS with different spatial resolution. For pathways this approach is less applicable due to the lack of linear features. Next, Guirado et al. (2017) bring machine learning a step further by concluding that Convolutional Neural Network CNN performs better than OBIA and therefore results in higher accuracies. However, combining the two methods delivers the best performance. Here CNN takes care of the detection and classification and OBIA for segmentation of areas.

Similarly to Guirado et al, Kazimi et al. (2018) wrote a very interesting article about machine learning. They compare three learning models: their own developed CNN, the VGG16 model and a stacked automated encoder (SAE) model. In their comparison they try to distinguish between tracks, streams, lakes and other. They encounter more or less the same issue as in the Leitha hills case study: that there is a difficulty to discern between tracks and streams. However, the curvature of streams may be a factor to make them more distinguishable. Kazimi et al. draw the intuitive conclusion that for a small width streams and tracks are better presented and with a larger one the lakes. The small non detectable features may remain an issue. Nevertheless, they can be of most interest as they can be relics of oldest tracks. The result of the comparison is that their own CNN model outperforms the other two. Simultaneously, Maxwell, Warner & Fang (2018) provide a state of the art of machine-learning methods with their pitfalls, strengths and useful applications. They acknowledge that lack of optimal use of ML is often based on insufficient knowledge. They argue among other points that the quality of the data plays an important role and it is important not to mix the training data with classification data to prevent overfitting. Further methods are discussed to improve the overall accuracy and classification accuracy. At the moment there is no machine learning method that is standing out for remote sensing data and the most suited application is case specific. Nevertheless, they foresee a great contribution of deep learning in the development of machine learning.

Next Lambers, Verschoof-van der Vaart, Bourgeois (2019) combine citizen science with deep learning. This deep learning application focused on Celtic field barrows and charcoaled kilns and is supposed to be the first multi-class detector classification. Unfortunately, pathways are not included. Their multi-class approach seems to contradict the vision of other researches to focus one object machine learning instead of multi (Sevara et al 2016, Davis 2018 Gallwey 2021).
Li et al. (2021) take deep learning a step further. The results published in this technical paper led to the conclusion that Sparse CNN is the best deep learning technique on available ALS in two case studies on large scale datasets. Notably, the deep learning seems also to perform better on small thin objects, like road segments, which with non-deep learning techniques are often misclassified. Computing memory, in another words computing time, is also investigated. Also, here Sparse CNN outperforms other applications.
Geometric classification can clash with use classification. For example Roman roads have different layouts in different part in Europe. So, gravel road could be a main Roman road somewhere and a secondary road in area with paved roads. In another words classification has to be adapted to its region.
Gradually decreasing the learning rate improves the model and the fact that the voxels approach outperforms a point-based approach are the lessons learned. At the same time, they conclude that gradually increasing receptive fields in encoding is beneficial. This results in effective learning for high-level features with surroundings. In the end more accurate predictions are possible. This surely accounts for objects difficult to capture by local geometric features.
Sparse CNN, as mentioned, is the best deep learning method. However, the reliance on training samples is still high. Further research should prove if this technique is applicable on features like historical roads and paths. Nevertheless, it seems promising.

Recently, articles from Fiorucci et al (2022) and Meyer-Heß et al. (2022) have been published. In both articles deep learning is applied, In the case of Fiorucci on burial mounds and Celtic fields, using a pixel based and geodetic centric approach as automatic evaluation measures for performance of detection; Meyer-Heß uses CNN on burial mounds and calculates their distance to hollow ways.

In contrast, in a legal article Bathaee (2018) takes a different point of view in, which he also explains the problems with black boxes in machine learning. Machine learning is too complex and its dimensions cannot be visualized to humans. For example, it could lead to the situation that machines can predict where roads have been, but we cannot understand why roads have been in certain place. In other words the problem is that machine learns but we do not. If so, we might miss the scope of research, which is to learn. In this way, only the reconstruction of historical trackways is possible. In reality interpretation and export knowledge are still of importance. Indeed, Bennett, Cowley & De Laet (2014) argue that automatic feature recognition should go hand in hand with expert knowledge. They affirm that there will be no algorithm that could replace expert knowledge in the future. Raczkowski (2021) agrees with their view and it is in line with the approach applied in the article about semi-automated extraction of road features published in AARG view (Vletter 2014).

10.2.3 Future research

As mentioned, the developed extraction method for the Leitha Hills worked quite well. Therefore, it is likely to function well in other medium size mountain areas, at least, in Europe. For flatter areas and especially flat sandy areas lesser results are to be expected.

Machine learning and artificial intelligence look very promising in this respect. It will be thrilling to see how models like the one of Li et al. will perform on the Veluwe and Leitha data sets. However, some time may be needed to develop a method which extracts very well and at the same time is capable of distinguishing between different kinds of roads and paths.

10.2.4 Research question and contribution to archaeology.

The sub research question to this methodological step was: “In how far can techniques for line extraction be used for a semi-automatic identification and mapping of roads and paths on ALS data?” The answer as proven in the articles of chapter 2 and chapter 3 clearly state that techniques for line extraction are very useful as they deliver an enormous time gain. Looking at the developments now and in the future (see 10.2.2 and 10.2.3) these techniques will only improve.

In this way the contribution to archaeological scientific field is substantial. Extraction and visualisation techniques allow to a better and faster research of historical roads and paths. Nevertheless, the human experience, eye and mind are still needed for understanding and interpretation of the results of the extraction applied.

10.3 – Chronological Models

The dating of roads and paths is intriguing and at the same time a complicated subject. This issue has been dealt with in chapter five. A distinction can be made between absolute and relative dating. In most of the cases only relative dating is possible. A relative chronological model was worked out for the Leitha Hills. This approach was not applied to the Veluwe. The amount of feature and their complexity made it unfeasible in the time available. Moreover, there was the possibility for absolute dating. Indeed, a segment of a cart track was absolutely dated.

10.3.1 Results and issue of the relative chronological model

A setback was that the flexible item-based OCHRE database presented in chapter five was not capable of dealing with the amount of data of the Leitha hills. Therefore, it was opted for ArcGIS to carry out the relative chronological dating.

Based mainly on the combination of interpretation of ALS and comparison of historical cadastral maps from around 1856, four periods can be distinguished for the Leitha hills. Modern roads built mostly long after 1856, roads before 1856 built and at the beginning of the 19th century, roads from probably the 18th or perhaps 17th century and some roads that most likely already existed earlier in the (late) mediaeval area.

The relative dating had three main complications, which are not unique for the Leitha hills but occur often. First, there was a strong impression that not all historical roads were mapped in the past. Second, modernized roads caused difficulty for interpretation. Third, the lack of accuracy on old (cadastral) maps created uncertainty.

Despite these issues, relative dating is applicable to the Leitha Hills and would be appropriate for similar middle mountain areas. However, two requirements are needed: good ALS data as well as detailed and accurate historical maps. For large areas like the

Leitha Hills, it has been quite laborious to create the chronological model. This is probably the reason that no similar research on this scale has been found.

3.2.1 Comparison of relative chronological models.

Relative dating in archaeology is widespread, especially applied to pottery, and is often based on the concept of the Harris matrix (Doneus et al 2022a, Doneus et al 2022b). This matrix tool is also digitally available (Traxler & Neubauer 2009). The relative dating of excavated roads is less common simply because roads and roads crossing are not often excavated. The relative dating of roads mostly happens based on visual interpretation of the intersection of roads, human artifacts, land-use, historical documents or geological processes (Beck 1991, Denecke 1967, Sheets & Sever 1991, Trombold 1991). Trombold acknowledges that these methods are far from watertight and discussion continues. For example, the finding a Roman coin does not make a road Roman. Even if sufficient statistic evidence of Roman artifacts is found, they do not tell if the Roman road was used before the Roman era. Despite these issues, relative dating can be very useful and gives insights in a chronology and often is the only way to date roads.

The elaboration of ALS data has improved the visualization of intersections and therefore the interpretation. Nevertheless, it often remains difficult to distinguish which road is older and which one is younger (see chapter five). Indeed, in an area of a dense and intertwined network of roads it can be sometimes better to group roads to make interpretation possible, as in the case of the Leitha hills. The complexity is also discussed by Mlekuž (2013). He finds landscapes and landscaping on ALS a messy affair. He states: 'There are discrete features but also the continuum of them, and there is no chronological succession but a mess of temporaries and by classifying landscape into simple well-ordered features we would just make a more mess out of it. So, the only way is to describe things as they are and produce accounts on how our practices of landscaping mingle with those of the past, no matter how messy these accounts might be'. Hesse (2013) encounters the same problem when he deals with the lidar dataset from Baden-Würtenberg. Nuninger et al. (2021) make use of cadastral maps to gain insight into the chronology of features in similar way to the Leitha research but on a smaller scale. They also encounter the difficulty of dating features found with lidar data.

10.3.3 Future research on relative dating

As mentioned above, relative dating of roads and paths is on a large scale is complicated. The developments regarding machine learning might reduce working time in the future. Despite the developments in machine learning (see above), it remains challenging to create a machine which is suited. Indeed, it should be capable of differentiating between features based on subtle characteristics and intersections to create a relative chronology. If, for example, a road crosses different landscapes, it might have different characteristics per segment, but still is one road (see also Veluwe case). Nevertheless, machine learning seems the way to reduce working time. However, the human understanding and interpretation must be leading (Opitz &Cowley 2013, Raczkowski 2021)

In the specific case of the Leitha Hills, the chronological model creates a basis for further deepening and improvement of the knowledge of the road and path system in the past. The model itself might be improved by further information, like incorporation of known dates of manufactures (bridges, statues, crosses, etc.) along the roads and paths. Again, these dates only provide a time which a road or path was probably in use.

10.3.4 Results and issues of absolute dating.

In the Veluwe, the absolute dating technique Optical Stimulated Luminescence (OSLS) was used for dating a cart track. OSL is only applicable when soil conditions are right. The results of the OSL dating showed a clear historical layering of wheel tracks in one wagon track of a hollow way bundle. The results lined up very well with historical sources. A large number of OSL samples should be taken from multiple wagon tracks for a complete understanding of the development of the bundle of hollow ways. However, this is an expensive exercise.

The OSL dating tells, of course, the last time a wheel track was in use. It doesn't tell us how long it has been used. This is a limitation of (OSL) dating. Combining the outcomes of different samples of different wheel tracks provides a completer image of the dynamics of the cart track investigated. It shows a possible use of it from the thirteenth until the beginning of the nineteenth century. However, prudence is required. First, the track was one of many in a bundle of cart tracks, meaning, it doesn’t tell anything about the other tracks. One might presume that lying next to each other the cart tracks date from more or less the same period. However, this is not supported by any evidence. Moreover, only a very small part of the complete route of about 60 kilometres has been investigated. Thus, it is very unreliable to extrapolate the results for the complete road.

The comparison with geological layers does not fit seamlessly with OSL. However, neither do they contradict. This is of importance to strengthen the outcomes of OSL dating (Kuzmina 2008). Moreover, the dating does line up with a period the starting of pavement of a lot of roads began at the beginning nineteenth century and thus the disuse of the cart tracks on sandy soils.

10.3.5 Comparison to other absolute dated roads.

A lot of OSL dating takes places in the geological field, where the technique has been developed. There are not many articles about absolute dating of roads as they are not often excavated on purpose. The combination of absolute dating and excavation is even less frequent. Clear examples of such a combination are carbon dating of wooden roads in (former) peat zones (Van der Sanden 2002, Brindley & Lanting 1998). Dendrochronology was applied in the investigation of a Roman road using wood and sapwood from a bridge and a dam (Linden van der et all 2016). Road tracks are sometimes dated in archaeological reports of excavation when roads are found by accident and goods samples are available for carbon dating. In other words, serendipity plays a role. A lot of archaeological reports are not published in international scientific journals. It is very likely that more absolute dating results are hidden in unpublished reports.

The cost is one of the reasons roads are not often definitively dated with OSL. Further, not all soils are suited for dating. A soil need minerals with radiation characteristics and sufficient long exposure to sunlight should have taken place. It is often not clear beforehand if a soil is suited and if soil samples are sufficient large enough for OSL dating.

A practical problem is that roads can stretch over a lot of kilometres. Again, an excavation tells something over a small part of a road. Next to it, excavation can be costly and time-consuming.

10.3.6 Future research

The above makes clear that the combination of OSL absolute dating and excavation of tracks carried out in the Veluwe is quite rare. Despite the mentioned issues the investigation of the cart track proved worthwhile. It provided insights about the genesis of the cart track and the geological processes involved. Thus, OSL dating of roads can be beneficial and more application should take place in other areas. Hopefully the absolute dating techniques evolve further making them easier in use and more economic. In this way, probably more and other trackways will be dated. This will also make comparison possible.

Regarding the specific case of the Veluwe, it could be of interest to excavate the cart tracks near the prehistoric mounds. Due to mainly administrative and time issues, it was not possible during the field work in the Veluwe.

Combining absolute dating with what Gibson calls “archaeology of movement” may be the best way to do physical research of historical pathways in the field. She applied archaeology of movement by carrying out a systematic transect field survey in a mountainous part of Cyprus. During this survey information about morphology, structural features, surface stability and environmental surroundings are recorded. Findings are structures along the roads and paths are used for dating and interpretation of use. Denecke (1969, 2007) has a similar view with his interdisciplinary approach for historical path ways. Another of the interesting subjects she deals with is tending, 'the routine act for caring for paths” (Gibson 2007).

10.3.7 Research question and contribution to archaeology

The sub research question regarding relative dating was : „What factors can be applied to determine the relative chronology of road networks and how can this visualised?“

Next to the known factors like historical sources, geological processes, human artifacts, and archaeological findings, Airborne Lasers Scan (ALS) also proved to be useful for dating. However, good resolution of ALS data and good visualisation techniques are essential, especially to visualize at crossing which roads runs over the other. Further, it needs to be stressed that relative dating could be complicated, especially regarding large areas with a lot of traces.

ALS combined with high quality historical cadastral maps made a visualisation of four periods in a GIS environment (ArcGIS) possible. Each layer can be visualised separately or together with other ones (with transparency) to make the development of the road system in the Leitha hills visible.

The Veluwe research made the extension of the research possible as absolute dating proved suitable. The absolute dating gave insights into the development of one single cart track in a bundle of tens of routes about 60 kilometres across a push moraine. Again, a GIS environment (ArcGIS) made the development of the excavated and dated cart track visible. That established that both the relative and the absolute OSL dating technique proved useful for historical road research.

The contribution of the investigation of relative dating and absolute dating to the archaeological scientific community is that both dating methods are feasible. Furthermore, they shed light on development of roads and path networks. The relative chronological model of the Leitha hills should be applicable to, at least, other hilly chalk stone areas in Europe. In this way knowledge and understanding of road and path networks in Europe can be increased.

The same accounts for the absolute dating. It provides insights in the dynamics of the use of roads over time. The carried-out research invites to further use of the OSL technique in other sandy areas in, at least, the northern sandy plains of Europe.

10. 4 – Results and issues of the reconstruction of roads.

In order to reconstruct vanished routes, predictive modelling based on least cost path (LCP) has been carried for both the Leitha Hills and the Veluwe. However, the needed resolution for soil or geological data sets were lacking the Leitha Hills for creating a good model. Therefore, in this area the focus lays on the investigation of the suitability gaming software for LCP modelling than the model itself. This model will be dealt with in the next section, gaming archaeology.

Regarding the Veluwe two predictive models were developed and compared to each other and to known historical road networks. The first model, the Network Friction Model (NFM), was developed by Rowin van Lanen (Lanen van et al. 2015). Van Lanen combines in an interesting way archaeological data with the environmental data on national scale. We followed up his research by investigating its applicability on a smaller regional scale in the Veluwe area.

The second model was a LCP model which incorporates the physical factors wetness, slope, and height. This model was developed on purpose for this area by the author.

The models were compared to each other on the basis of overlap with the 1600 road maps, roads on the military map of 1850 and the wagon and cart tracks on the ALS visualisation. Both models line best up with the 1850 map and to a lesser extent to the 1600 road map. The higher density of roads of the former map influenced the outcome. However, both models did not line up very well with cart and wagon tracks on the ALS visualisation, despite the quite density of these tracks in the study area. An explanation for this divergence is not clear. The wagon and cart tracks may for a large part be local tracks which do not fit the long distance (regional) modelling of the models.

Both models were complimentary in finding routes, as sometimes the NFM performed better and sometimes the LCP model. However, in general the NFM lines better up than the LCP model does. This supports the theory that cultural factors also influence the routing. The strength of the LCP was that it demonstrated that dominating physical factors influencing the investigated routes could differ a lot per route, meaning that in general, it is complicated to make a model to capture all routes in an area accurately.

In the end, the predictive modelling delivered interesting results. However, it needs to be stressed that predictive modelling for roads and routes remains a very complicated matter. Nevertheless, the results invite for further investigation.

10.4.2 Comparison to other reconstruction models or techniques.

Nakoinz and Knitter (2016) give a good and pleasant readable overview of the basics of modelling of human behaviour in general in archaeology. Predictive modelling of pathways for reconstruction is one way of modelling of human behaviour and is widespread in archaeology, especially based on LCP. In this subparagraph issues regarding this kind of modelling are dealt with.

Looking at LCP function to reconstruct a route, Parcero-Oubiña et al. (2019) discuss rightfully that a good knowledge of the cost factors must be taken into account too. The cost factors differ from region to region. In our research (2018) we have made clear that crossing a push moraine in different ways changes the factors which have most influence over the route. Indeed, good understanding of the cost factors and their digital translation are crucial to create an LCP model for reconstruction historical pathways. For validation of the model remnants of historical roads or digitised historical maps are very suited (Güimil-Fariña & Parcero-Oubiña 2015). Herzog (2014) agrees with this notion and sees validation as the most important step of LCP models. However, she proves through the application of a Delauny triangulation of places how distorted historical maps can be, making validation difficult. This often occurs with maps before the 19th century. This and the fact that it is difficult to rectify such maps are the reasons these maps have been left out in the Veluwe research.. Herzog finds in her research areas that avoiding wet areas in combination of slopes lower than 17% are the main factors for long trade routes. More or less the same came out of the LCP model for the Veluwe, where wet areas formed the main factor determining the routes. Especially for wet and flat areas of the (historical) Dutch landscape this is not a surprise. Despite the situation for the sandy push moraines of the Veluwe, this is not always the case. In her research Herzog shows that trial and error is sometimes needed to find the right value of cost factors influencing a pathway. This lines up with the experience of optimizing the LCP model for the Veluwe.

Verhagen et al. (2019) make an interesting point about safety influencing pathways in the past, which isa theme that is not often dealt with. They rightly state that safety is difficult to model. Further they discuss effective slope, meaning the slope in direction of movement. Therefore, anisotropic movement is needed as ascending a slope is different as descending. However, a lot of pathways are modelled with the same cost function in both directions.

Beside the direction also the beginning and the end point of pathways are of importance. Fábrega-Álvarez (2006) proposed the interesting theoretical idea to create paths without defined fixed end point. Many models are based on fixed end and beginning points, which is logical if they are known. However, the beginning and the end of routes are not always known.

Also, cultural change plays a role. For example, in the same area of Egypt the roads from Graeco-Roman times followed mostly the orientation of the wadis, in other words the natural landscape. The Romans in a later period preferred to build instead linear roads there. There is no clear explanation for this (Gates 2006)

Llobera instead deals with the socialisation aspect of movement. An interesting point of his is that monuments could affect movement. The effects can be divided in repel and attraction. Both change the course that would only be based on surface cost. The incorporation of monuments in his GIS model shows the complication and limitedness of translating social behaviour in digital model (Llobera 2000).

Alternatively, Mlekuc, provides an interesting case with time geography, in which geography "focuses on time, space and practices, and places the emphasis on the significance of the material world and its constraints." An interesting outcome of his research was that long distance travel forms the landscape in a different way then day to day travel (Mlekuž, D. 2014). This may explain why the models of the Veluwe do not line up very well with short tracks on the ALS model if the latter represents local short distance travel. Next, Howey (2011) applies circuit theory for pathfinding applied to Indian landscape in the USA. She uses water, vegetation and slope as criteria for cost surface in her model and further notes that the software used was computation intensive. The reason for applying circuit theory is that LCP modelling is not able to carry out multipath modelling, leading to one optimum solution. This does not reflect reality as individual variations exist to reach a certain place. Circuit theory covers this flaw by allowing multiple pathways. In the model connectivity is quantified positively if alternative pathways are available. This is both its strength and weakness, as acknowledged by the author. On the one hand, it allows us to look at alternative pathways, and on the other hand, it may minimize a clear distinct route. Therefore, a complementary approached is suggested. Murgatroyd et al. (2012) used computer-intensive Agent Based Modelling to model the logistics and most probable marching route of Byzantine troops on their way to the lost battle of Manzikert. These researchers make use of the possibility to choose different routes for multiple agents. The use of multiple agents on a large landscape scale makes the model quite unique. The visualisation of this model is very intuitive and helps to understand the movements.

Finally, Nuninger et al. (2020) give a good overview of the use of ALS for researching movement. Their focus lays on interoperability suggesting the use of a heuristic tool based on ontology to develop a cross-cultural framework. Hereby making an interesting link between ALS data on the one hand and the modelling of movement on the other. From a methodological point of view, this technological effort should be coupled to a systematic description of the data, analytical process, sensitivity analysis, and validation.

10.4.3 Future research

Rączkowski (2020) discusses the limitations of models, including LCP, including the fact that they can never equal reality and therefore a complete understanding of the subject of study is never possible. He advocates therefore a more holistic approach including fieldwork, historical sources and the natural (historical) environment. Models should be technically understood and different models combined. Further, for obtaining results they should be simple and feasible.

He stresses clearly that despite the fast-developing technologies occurring in archaeology the basis of the research remains human based. Therefore, cultural objectivity cannot be obtained. He also warns about the danger of stopping thinking if we rely too much on the technical approach. This point is also made in Bathaees article about black boxes (2018).

As mentioned above, modelling to reconstruct pathways is quite complex. To incorporate all factors may be impossible. The best way to go may be to keep models simple and feasible, as argued by Rączkowski (2020).

Despite the complexity, models can lead to a better understanding of the landscape and thus they are useful. Therefore, we should continue to create models, combining, comparing and validating them. In the specific case of the Veluwe, the created models could be further fine tuned

Ontology is an interesting research field and might lead to a cross-cultural framework, as suggested by Nuninger et al. However, it might be the case to look further than the often-used 3D-models in a GIS environment. Indeed, the gaming engines may open the door to more possibilities and thus a better understanding of historical pathways. This topic will be dealt with in paragraph 10.5.

10.4.4 Research question & contribution to archaeology

The sub research question for this section was; “What model based on landscape characteristics with found networks can help us predict paths in order to complete missing part of our network?”

From the research it is clear that both (historical) environmental and archaeological data can help to predict where former pathways have been. Especially the combination of models help to find vanished routes as the research makes clear that there is no model so far which is able to predict all kind of routes. This is understandable as the routes often have different layouts as the landscape changes. Moreover some aspect of human movement, like safety, are hard to model. Therefore, the objective of the model must be clear and directed toward this objective. Nevertheless, the produced models invite further research, improvement, and gave insights into human movement.

10. 5 – Gaming archaeology

10.5.1 Results and issues of applying a gaming engine for historical road and path research

The gaming engine Unity was investigated for its utility for historical roads and paths research. The reconstruction of a landscape through the import of a height model based on ALS data is possible. Due to the available assets in Unity the landscape can be reconstructed more realistically. Multiple agents can be imported. A time element makes it possible to create different landscapes for different periods. The A* script is suited to analytical investigations of movement. Indeed, the simple least cost paths made in ArcGIS lined up quite well with the ones in Unity. The potential of gaming engines for reconstruction and analytical are therefore present. However, some issues are still limiting its current possibilities. Processing power is one of these issues. Sufficient processing power is needed to carry out the rendering of complicated scenes with large surface areas and to calculate the movement within. However, the on-going increase of processing power could resolve this in the (near) future. Further, to achieve in-depth analytics, scripting knowledge is needed. A lot of researchers lack this knowledge. However, this could also be a matter of time. Nowadays, programming skills are becoming more part of (art and) science education.

Despite these current drawbacks, gaming engines already show their power of visualisation and embodiment of the landscape. I believe the future of gaming engines for historical landscape research is promising.

10.5.2 Comparison to other applied game engines for road research.

There are a lot of historic games, and there exists also the discipline of archaeogaming. However, most of the time these are created worlds not based on the historical landscape. Therefore, they are of limited use for reconstruction and investigation of historical pathways. At the time of writing, no comparable literature to the specific use of gaming engines for historical roads and paths research was found. Nevertheless, developments in the field of archaeology and historical landscape research are taking place. For example, a very interesting PhD thesis dealing with a broad range of issues regarding the use of videogaming for archaeology was written by Reinhard in 2019. Interestingly, he takes a different point of view of designing a new world to learn for archaeological purposes instead of reconstruction. Indeed, he actually plays a game and creates everything within the gaming environment: making maps for GIS, georeferencing, making 3D artifacts, finding “crop marks” etc., instead of bringing the landscape and archaeology into the gaming world. Making reports of videos of the experiences of the landscape in game could contribute to a better understanding of the historical landscape. It clearly shows the enormous possibilities in gaming engines.

The author does not deal explicitly with travelling or roads within the game-environment. Nevertheless, he experiences the maps as natural and organic when he travels through the created world. In his game, one player only has control of changes, no changes made by others.

The author mentions a number of issues when using gaming engines. The level of detail is such an issue. One must consider which level of detail is needed. Regarding road and path research seeing sand grains is not necessary for exploration in a gaming environment. On the other hand, it must look sufficiently realistic for investigation and experiencing the landscape

Accessibility is another important issue. Enhanced accessibility to games and their tools would make it useful for everybody. Nowadays costs and availability of tools (VR headsets) are limiting factors. (Reinhard 2019).

Ch'ng and Gaffney (2013) instead recreated a large-scale Mesolithic landscape Doggerland in the (then not existing) Nord Sea. Information from several disciplines was gathered to recreate this landscape in a gaming engine. A next step was to walk around with an avatar, a Mesolithic person in this world.

10.5.3 Future research

The use of gaming engines for historical roads and paths is still in its infancy. I agree with Edgeworth, who said in 2014: “if probed with skill and discernment, the virtual landscape can potentially yield an almost infinite number of new discoveries, each one giving rise to further paths of exploration that can be followed towards further discoveries and insights” (Edgeworth 2014, p. 19). Due to its complexity it is understandable that archaeology is not a forerunner in the use of gaming engines. However, the broad use of gaming nowadays in society and scientific research gives the impression that archaeology is lagging behind a bit, especially regarding historical road and paths research. For example, in the work of Verhaegen Nuninger & Groenhuijzen (2019) the application of gaming software and all its (future) possibilities was not mentioned. Nevertheless, this is a field where a lot of (commercial) development is going on, from which the science could benefit. Also, in the field of historical road research. I believe that many topics of this dissertation can be dealt with in the future by using gaming engines. In addition, Ch'ng (2009) wrote another interesting article, this time about virtual time travelling. He investigated the recreation of an archaeological sites and the possibility to feel, smell and hear at the same time. He reckons that in the future virtual time travel for experimental archaeology will be possible and the only physical limitations for humans are time and place.

10.5.4 Research question and contribution to archaeology

The research question for this section was: “How can the development of road and path networks over time and space be visualised?”

This question was already partly answered by the discussion about the relative chronology above. Here a GIS environment proved worthwhile to visualise the development of the road system in the Leitha hills. However, this is quite a static model.

Gaming engines provide, like the slider function in Unity, a possibility to change landscapes coupled to a certain period. The applicability of this function is quite straightforward.

A more challenging question was if roads and paths could be predicted in a similar way as is feasible in GIS environment. Therefore, the focus shifted in this direction. This led to the conclusion that a simple LCP in Unity compared to one in a GIS environment had indeed similar outcomes, though improvements in the gaming software, like the enhancement of resolution, are needed. However, increasing resolution will lead to more computing time. Nevertheless, the ongoing developments of the gaming software will probably resolve this issue in the (near) future. Gaming engines certainly offer a lot of possibilities in embodiment and thus the experience of the landscapes, which are not possible in a GIS environment. Therefore, research of historical pathways in gaming engines looks very promising.

The contribution to archaeology of the investigation of gaming engines for historical pathways research is that they are worthwhile and promising. However, to reach high quality results, programming knowledge is recommended. Indeed, to have full control over game one should be able to influence characteristics of the game. The best way to do this is writing or adapting the programming languages so the specific research objectives can be optimized.

10. 6 Final conclusion

Concluding remarks about the methodology developed.

In the end, the conclusion is that in general for both research areas that the methodology worked well. Indeed, all steps contributed to historical road research and therefore increased our understanding of historical road networks in both areas. However, for both areas the applicability differed due the lack of good data sets or the difficulty of the landscape. Indeed, a general point that comes back in all steps is the importance of good datasets. It is clear that good ALS data forms the basis of successfulness of the methodology. Its application to other areas and improvement of the methodology are important next steps.

Literature

Bathaee, Y. (2018). The Artificial Intelligence Black Box and the Failure of Intent and Causation. *Harvard Journal of Law Technology,* 31, 889–938.

Beck, C. (1991). Cross-cutting relationships: The relative dating of ancient roads on the north coast of Peru. (Trombold, C. D., Ed.) *Ancient road networks and settlement hierarchies in the New World.* 66-79

Bennett, R., Cowley, D. & De Laet, V. (2014). The data explosion: Tackling the taboo of automatic feature recognition in airborne survey data. *Antiquity,* 88, 896–905.

Blaschke, T. & Strobl, J. (2001). What's wrong with pixels? Some recent developments interfacing remote sensing and GIS. *Geobit/Gis* , 6, 12–17.

Brindley, A. L. & Lanting, J. N. (1998). Radiocarbon Dates for Irish Trackways. *The Journal of Irish Archaeology*, *9*, 45–67. http://www.jstor.org/stable/30001692

Ch'ng, E. (2009). Experiential archaeology: Is virtual time travel possible? *Journal of cultural Heritage, 20*, 458-470.

Ch'ng, E., Gaffney, V.L. (2013). Simulation and Visualisation of Agent Survival and Settlement Behaviours in the Hunter-Gatherer Colonisation of Mesolithic Landscapes. In: Ch'ng, E., Gaffney, V., Chapman, H. (eds) Visual Heritage in the Digital Age. Springer Series on Cultural Computing. Springer, London. https://doi.org/10.1007/978-1-4471-5535-5_12

Davies, D.S., Sanger, M.C. & Lipo, C.P. (2019). Automated mound detection using lidar and object-based image analysis in Beaufort County, South Carolina. *Southeast. Archaeology*, 38, 23–37.

Davis, D. S. 2019. Object-based image analysis: a review of developments and future directions of automated feature detection in landscape archaeology. *Archaeological Prospection* 26 (2), 155–163. DOI: 10.1002/arp.1730

Denecke, D. (2007) Wege und Wegenetze. In: *Reallexikon der Germanischen Altertumskunde* 35. Berlin: de Gruyter, 626–648

Denecke, Dietrich (1969): Methodische Untersuchungen zur historisch-geographischen Wegeforschung im Raum zwischen Solling und Harz. Ein Beitrag zur Rekonstruktion der mittelalterlichen Kulturlandschaft. – Göttingen.

Doneus, M. (2013). Die hinterlassene Landschaft Prospektion und Interpretation. Die Landschaftsarchäologie in Mitteilungen der Prähistorischen Kommission, 78. Vienna: OAW. DOI: https://doi. org/10.2307/j.ctt1vw0qcb

Doneus, M., Doneus, N., Cowley, D., (2022a). Confronting Complexity: Interpretation of a Dry Stone Walled Landscape on the Island of Cres, Croatia. *Land* (11), 1–43.

Doneus, M., Neubauer, W., Filzwieser, R., Sevara, C. (2022b). Stratigraphy from Topography II - The practical application of the Harris Matrix for the GIS-based spatio-temporal archaeological interpretation of topographical data. *Archaeologia Austriaca*, 106, 223–252.

Edgeworth, M. (2014). From spade-work to screen-work: new forms of archaeological discovery in digital space. In: A. Carusi, A. Sissel Hoel, T. Webmoor and S. Woolgar (Eds.) *Visualization in the age of computerization*,. London, Routlegde, 40-58.

Fábrega-Álvarez, P. (2006). Moving without destination. A theoretical GIS–based determination of movement from a giving origin. *Archaeological Computing Newsletter*, 64: 7–11.

Fiorucci, M., Vaart, W. B. V.-van der , Soleni, P., Saux, B. L., & Traviglia, A. Deep Learning for Archaeological Object Detection on LiDAR: New Evaluation Measures and Insights. *Remote Sensing*, 14(7), 1694. https://doi.org/10.3390/RS14071694

Gallwey, J., Eyre, M., Tonkins, M. and Coggan, J. (2019). Bringing Lunar LiDAR Back Down to Earth: Mapping Our Industrial Heritage through Deep Transfer Learning. *Remote Sensing* 11 (17), 1994; https://doi.org/10.3390/rs11171994

Gates, J.E. (2006). Hidden passage: Graeco-Roman roads in Egypt's eastern desert. In: E.C. Robertson, J.D. Seibert, D.C. Fernandez and M.U. Zender eds. *Space and Spatial Analysis in Archaeology*. Calgary: University of Calgary Press, 315–322. DOI: https://doi. Org/10.2307/j.ctv6gqr9h.35

Gibson, E. (2007). The Archaeology of Movement in a Mediterranean Landscape. *Journal of Mediterranean Archaeology*, 20(1), 61–87. DOI: https://doi.org/10.1558/jmea.v20i1.61

Güimil-Fariña, A and Parcero-Oubiña, C. (2015). Dotting the joins: a non-reconstructive use of Least Cost Paths to approach ancient roads. The case of the Roman roads in the NW Iberian Peninsula. *Journal of Archaeological Science*, 54, 31–44. DOI: https://doi.org/10.1016/j.jas.2014.11.030

Guirado, E., Tabik, S., Alcaraz-Segura, D., Cabello, J., Herrera, F. (2017). Deep-learning Versus OBIA for Scattered Shrub Detection with Google Earth Imagery: Ziziphus lotus as Case Study. *Remote Sensing*, 9, 1220.

Herzog, I. (2013). Theory and Practice of Cost Functions. In: F. Contreras, M. Farjas, M and F. J. Melero, eds. *Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010*. *BAR International Series*. Oxford: Archaeopress, 375–382.

Herzog, I. (2017). Reconstructing Pre-Industrial Long-Distance Roads in a Hilly Region in Germany, Based on Historical and Archaeological Data. *Studies in Digital Heritage*, 1(2), 642-660. DOI: 10.14434/sdh.v1i2.23283

Hesse, R. (2013). The changing picture of archaeological landscapes: lidar prospection over very large areas as part of a cultural heritage strategy. In R. Opitz, R and D. Cowley, D., eds. *Interpreting archaeological topography: lasers, 3D data, observation, visualisation and applications*, Oxford: Oxbow books, 171–183. DOI: https://doi.org/10.2307/j.ctvh1dqdz.19

Howey, M. C. L. (2011). Multiple pathways across past landscapes: circuit theory as a complementary geospatial method to least cost path for modelling past movement. *Journal of Archaeological Science* 38 (10), 2523–2535.

Kazimi, B., Thiemann, F., Malek, K., Sester, M., Khoshelham, K. (2018) Deep Learning for Archaeological Object Detection in Airborne Laser Scaning Data. 2018) In: A Belussi, R. Billen, P. Hallot, S. Migliorini. Eds. *Proceedings of the 2nd Workshop on Computing Techniques for Spatio-Temporal Data in Archaeology and Cultural Heritage*, Melbourne, Australia, 25–28 August 2018;. 21–35.

Kokalj, Ž., Somrak, M. (2019). Why Not a Single Image? Combining Visualizations to Facilitate Fieldwork and On-Screen Mapping. *Remote Sensing*, *11*(7), 747. https://doi.org/10.3390/rs11070747

Kuzmina, E. E. 2008.The prehistory of the silk road. University of Pennsylvania Press.

Lambers, K., Verschoof-van der Vaart, W., & Bourgeois, Q. (2019). Integrating Remote Sensing, Machine Learning, and Citizen Science in Dutch Archaeological Prospection. *Remote Sensing*, *11*(7), 794. https://doi.org/10.3390/rs11070794.

Li, N., Kähler, O., & Pfeifer, N. (2021). A comparison of deep learning methods for airborne lidar point clouds classification. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *14*, 6467-6486. DOI: 10.1109/JSTARS.2021.3091389.

Llobera, M. (2000). Understanding movement: a pilot model towards the sociology of movement. In: G. Lock, G ed. *Beyond the Map. Archaeology and Spatial Technologies. NATO Science Series. Series A: Life Sciences*. Amsterdam: IOS Press/Ohmsha, 66–84.

Maxwell, A.E., Warner, T.A., Fang, F. (2018) Implementation of machine-learning classification in remote sensing: An applied review*. International Journal of Remote Sensing,* 39, 2784–2817.

Meyer-Heß, M. & Pfeffer, I & Jürgens, C. (2022). Application of Convolutional Neural Networks on Digital Terrain Models for Analyzing Spatial Relations in Archaeology. *Remote Sensing*. 14. 10.3390/rs14112535.

Mlekuž, D. (2013). Messy landscapes: lidar and the practices of landscaping. In: R. S. Opitz, RS and D.C. Cowley, DC (eds.), *Interpreting archaeological topography. 3D data, visualisation and observation. AARG Occasional Paper*. Oxford: Oxbow Books, 88-99. DOI: https://doi.org/10.2307/j.ctvh1dqdz.12

Mlekuž, D. (2014). Exploring the topography of movement. In: S. Polla, and P. Verhagen, (Eds.), *Computational Approaches to the Study of Movement in Archaeology. Theory, Practice and Interpretation of Factors and Effects of Long-Term Landscape Formation and Transformation*. Topoi – Berlin Studies of the Ancient World/Topoi – Berliner Studien der Alten Welt. Berlin: De Gruyter, 5–22.

Murgatroyd, P. (2013). Visualising Large-Scale Behaviours: Presenting 4D Data in Archaeology. In: Ch'ng, E., Gaffney, V., Chapman, H. (eds) *Visual Heritage in the Digital Age*. Springer Series on Cultural Computing. Springer, London. https://doi.org/10.1007/978-1-4471-5535-5_13

Nakoinz, O., & Knitter, D. (2016). Modelling human behaviour in landscapes. *Basic Concepts and Modelling Elements. Cham, Springer.*

Nuninger, L., Opitz, R., Verhagen, P., Rouge, T. L., Laplaige, C., Leturcq, S., Le Voguer, N., Fruchart, C. Kokalj, Ž. & Rodier, X. (2020). Developing FAIR ontological pathways: linking evidence of movement in lidar to models of human behaviour. *Journal of Computer Applications in Archaeology*, *3*(1), 63-75. https://doi.org/10.5334/jcaa.46

Parcero-Oubiña, C., Güimil-Fariña, A., Fonte, J.and Costa-García, J.M. (2019). Footprints and Cartwheels on a Pixel Road: On the Applicability of GIS for the Modelling of Ancient (Roman) Routes. In: P. Verhagen, J. Joyce & M. R. Groenhuijzen (Eds.), *Finding the Limits of the Limes*, Computational Social Sciences, 291-311. https://doi.org/10.1007/978-3-030-04576-0_14

Rączkowski, W. (2020). Power and/or penury of visualizations: Some thoughts on remote sensing data and products in archaeology. *Remote Sensing*, *12*(18), 2996.

Reinhard, A. D. (2019). *Archaeology of digital environments: tools, methods, and approaches* (Doctoral dissertation, University of York).

Sanden, W.A.B van der. (2002). Veenwegen in Drenthe: enkele nieuwe dateringen. *Nieuwe Drentse Volksalmanak* 119, 101-112

Sevara, C., Pregesbauer, M., Doneus, M., Verhoeven, G., & Trinks, I. (2016). Pixel versus object—A comparison of strategies for the semi-automated mapping of archaeological features using airborne laser scanning data. *Journal of Archaeological Science: Reports*, *5*, 485-498.

Sheets P. and Sever, T. L. (1991). Prehistoric footpaths in Costa Rica: transportation and communication in a tropical forest. In Trombold. C. D. (Ed.): *Ancient Road Networks and Settlement Hierarchies* in the New World, 53-65. Cambridge University Press.

Traxler, C., & Neubauer, W. (2008). The Harris matrix Composer—A New Tool to Manage Archaeological Stratigraphy. In *Archäologie und Computer-Kulturelles Erbe und Neue Technologien-Workshop* (13) 3-5.

van der Linden, M., Jansma, E., van Daalen, S., & Lange, S. (2016). Absolute dating of the Roman Road near Bunnik, the Netherlands. *STR16/04*, 6.

van Lanen, R. J., Kosian, M. C., Groenewoudt, B. J., Spek, T., & Jansma, E. (2015). Best travel options: modelling Roman and early-medieval routes in the Netherlands using a multi-proxy approach. *Journal of Archaeological Science: Reports*, *3*, 144-159.: https://doi.org/10.1016/j.jasrep.2015.05.024

Verhagen, P., & NUNINGER, L. (2019). Verhagen, P., L. Nuninger & M.R. Groenhuijzen (2019). Modelling of Pathways and Movement Networks in Archaeology: An Overview of Current Approaches. In: Verhagen P., Joyce J., Groenhuijzen M. (eds) Finding the Limits of the Limes, pp. 217-249. Computational Social Sciences, Simulating the Past (Springer, Cham), 217–249. https://doi.org/10.1007/978-3-030-04576-0_11

Verhagen, P., Nuninger, L., and Groenhuijzen, M. R. (2019). Modelling of pathways and movement networks in archaeology: an overview of current approaches. In: Verhagen, P, Joyce, J and Groenhuijzen, MR (eds.), *Finding the Limits of the Limes: Modelling Demography, Economy and Transport on the Edge of the Roman Empire*. Cham: Springer, 217–249. https://doi.org/10.1007/978-3-030-04576 -0_11

Vletter, W. F. (2014). (Semi) automatic extraction from Airborne Laser Scan data of roads and paths in forested areas. In *Second International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014)* (Vol. 9229, pp. 400-410). SPIE.

Appendix 1 English Abstract

The main aim of the dissertation is to develop a methodology for the reconstruction of road and path networks based on ALS data. Basic research has been tested in two different case-study areas with different landscape settings on an interdisciplinary basis. The central research question has been: What are the possibilities of large-scale ALS data for the reconstruction of (pre-) historic road and path networks? The underlying objective has been to develop a methodology to use ALS data for historical road and path research, which is applicable in different areas of Europe or even the world. Reconstructing path networks needs to follow several basic steps: identification of paths, mapping of paths, creating a (relative) chronological model of the mapped instances, reconstructing paths in void areas, validating the results, and finally the visualisation and discussion of the results. In the end, the conclusion is that in general for both research areas that the methodology worked well. Indeed, all steps contributed to historical road research and therefore increased our understanding of historical road networks in both areas. However, for both areas the applicability differed due the lack of good data sets or the difficulty of the landscape. Indeed, a general point that comes back in all steps is the importance of good datasets. It is clear that good ALS data forms the basis of successfulness of the methodology. Its application to other areas and improvement of the methodology are important next steps. The developments of technical tools like deep learning, optical stimulated luminescence and gaming engines look promising in this regard. Nevertheless, the human understanding and interpretation must be leading in all applications for historical road and path research.

Appendix 2 Deutsche Zusammenfassung

Das Hauptziel der Dissertation ist die Entwicklung einer Methodik zur Rekonstruktion von Straßen- und Wegenetzen auf Basis von ALS-Daten. Die Grundlagenforschung wurde interdisziplinär in zwei unterschiedlichen Fallstudiengebieten mit unterschiedlichen Landschaftssettings erprobt. Die zentrale Forschungsfrage lautete: Welche Möglichkeiten bieten großräumige ALS-Daten zur Rekonstruktion (vor-)historischer Straßen- und Wegenetze? Das zugrunde liegende Ziel war die Entwicklung einer Methodik zur Verwendung von ALS-Daten für die historische Straßen- und Wegeforschung, die in verschiedenen Gebieten Europas oder sogar der Welt anwendbar ist. Die Rekonstruktion von Pfadnetzwerken muss mehreren grundlegenden Schritten folgen: Identifizierung von Pfaden, Kartierung von Pfaden, Erstellung eines (relativ) chronologischen Modells der kartierten Instanzen, Rekonstruktion von Pfaden in leeren Gebieten, Validierung der Ergebnisse und schließlich Visualisierung und Diskussion der Ergebnisse. Am Ende lautet das Fazit, dass die Methodik im Allgemeinen für beide Forschungsbereiche gut funktioniert hat. Tatsächlich trugen alle Schritte zur historischen Straßenforschung bei und erweiterten daher unser Verständnis historischer Straßennetze in beiden Bereichen. Allerdings unterschied sich die Anwendbarkeit für beide Gebiete aufgrund des Mangels an guten Datensätzen oder der Schwierigkeit der Landschaft. Ein allgemeiner Punkt, der in allen Schritten wiederkehrt, ist die Bedeutung guter Datensätze. Es ist klar, dass gute ALS-Daten die Grundlage für den Erfolg der Methodik bilden. Seine Anwendung auf andere Bereiche und die Verbesserung der Methodik sind wichtige nächste Schritte. Die Entwicklungen technischer Tools wie Deep Learning, optisch stimulierte Lumineszenz und Gaming-Engines sehen in dieser Hinsicht vielversprechend aus. Dennoch muss bei allen Anwendungen zur historischen Straßen- und Wegeforschung das menschliche Verstehen und Interpretieren führend sein.

Acknowledgements

I would like to thank the first of all my supervisors, Michael Doneus and Theo Spek, for guiding me through my PhD research. With his critical scientific view Michael gave the support I needed. Theo, being the “Johan Cruyff” of historical landscape research is always inspirational and he was so kind to offer me a working place in Groningen. Further I would like to thank the Vienna Institute of Archaeological Science and the Ludwig Boltzmann Institute for Archaeological Prospection for the support they gave. In this regard of course I need especially name the director Wolfgang Neubauer, who, together with Michael, organised the PhD programme very well.

I would also like to thank my colleagues of the IC-Program. The fieldtrip to Santorini was an unique experience. I will never forget the team spirit during the seismological investigations. A special thank goes to colleague Eammonn Baldwin, neighbour Timothy Jelfs and team mate Abhirup Bhattacharya for checking my English texts. Eammonn learned me also, during my internship in Birmingham, the importance of focusing. Jakob Kainz was very helpful to make financial transactions possible from university of Vienna. With Crhistopher Sevara I had interesting intellectual conversations, like the one about the hieroglyph with the fish at the entrance of the institute. Together with him, Jakob and Martin Ferra we made a remarkable trip to Duke University in the United States, were a philosophical cab driver advised me wisely to stay who I am, Dutch. Further I need to thank Katalin Tolnai for helping me with small but important (bureaucratic) issues of the PhD programme. Finally, I would like to thank Rog Palmer for the inspiration he gave me to produce an award winning poster.