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BRIDGING THE GAP: DIGITAL MODELS OF HISTORIC ROOF STRUCTURES FOR ENHANCED INTERDISCIPLINARY RESEARCH

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Abstract

The paper describes a project to generate digital 3D geometric and structural models of historic roof structures made of timber in a highly automated way directly out of 3D laser scan data. Within an interdisciplinary workflow, the new approach provides digital data of the timber structures in formats which can be used easily for both, the subsequent architectural analysis and the structural assessment. Compared to conventional methods, the project aims to replace labour intensive manual work of 3D documentation and modelling of historic roof structures by a time-saving digital workflow enabling straight exchange of data and results between surveyors, architects and structural engineers.

Keywords

Integrating architectural and structural modelling, 3D-scan data processing and modelling, Historic timber structures, Heritage documentation, Digital reconstruction

1. *Introduction*

Research, but also planning on adaptive reuse, maintenance and restoration of historic timber structures requires extensive architectural and structural analysis of their present condition. Current methods for a digital modelling of roof constructions consist of several manual steps including the time-consuming dimensional modelling for the presentation of the construction type or the hypothetical process of assembly as typical results of such studies. The continuous development of terrestrial laser scanners increases the accuracy, comfort and speed of the surveying work in roof constructions. Resulting point clouds enable detailed visualization of the constructions represented by single points or polygonal meshes, but in fact do not contain necessary information about the structural system and the characteristics of the beam elements themselves. That's what we call the "gap" in the following article.

However, the geometric model, as well as additional information about the structural properties of involved wooden beams and their joints, is necessary input for a further comprehensive structural modelling of timber constructions and the use of existing powerful engineering software tools. The contributions of this article are the description and discussion of a current project`s approach for bridging the gap between these different characters of information. The project involves institutes of three faculties at TU Wien and aims to develop a method to generate special types of digital 3D structural models of historic roof structures made of timber in a highly automated way directly out of 3D laser scan data[1].

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[1] The project *Points – Beams – Structures. Generating Digital Structure Models out of 3D Laser Scan Data for Structural Assessment and Architectural Analysis of Historic Timber Structures"* is under conduction at TU Wien in cooperation of the Institute of History of Art, Building Archaeology and Restoration, Research Group History of Architecture and Building Archaeology (Prof. M. Döring-Williams), the Department of Geodesy and Geoinformation, Research Unit of Photogrammetry (Prof. N. Pfeifer), and the Institute of Mechanics of Materials and Structures, Research Unit of Simulation of Materials and Structures (project responsibility: G. Hochreiner). It is funded by TU Wien in the frame of the Innovative Projects-Call 2017.

(Pöchtrager, Styhler-Aydın, Döring-Williams, & Pfeifer, 2018; Pöchtrager, Styhler-Aydın, Döring-Williams, & Pfeifer, 2017) While the previous publications mainly dealt with the geometric modelling of timber structures from point clouds, this article deals with the development of an integrated workflow for the documentation of historic roof structures including the exchange of results about the structure, gained during the interdisciplinary assessment.

1.1 Status quo: Architectural documentation and analysis of historic roof structures

The deformation-accurate survey and detailed documentation of historic roof structures made of timber form the basis for their analysis. While the main part of this article focuses to the automatic generation of digital 3D models out of point clouds of timber structures, the following overview shall inform on the entire work process and the type of data collected in general during the study in historic roofs. It motivates our methodological advances and also the data structures used.

Current surveys are being elaborated combining high-tech and traditional documentation techniques including terrestrial laser scanning (Fig. 2). (Eßer, Styhler-Aydın, & Hochreiner, 2016) The proven workflow developed and conducted by the team of the TU Vienna Research Group History of Architecture and Building Archaeology provides the following results (Fig. 1):

- Detailed survey (plans, sections, details of joints), including dendrochronological analysis.
- Catalogue of substructures attached to the system of rafters (for the systematical compilation of all information and features).
- Detection and systematical recording of carpenter`s marks.
- Classification in terms of typology, structure, construction period(s) and carpenter`s knowhow.
- Based on all results a hypothetical virtual reconstruction of the process of assembly.
- Written description and explanation of all features, results, reconstructions etc. including a list of sources.

In a next step, the accurate geometrical and historical analysis and documentation is handed

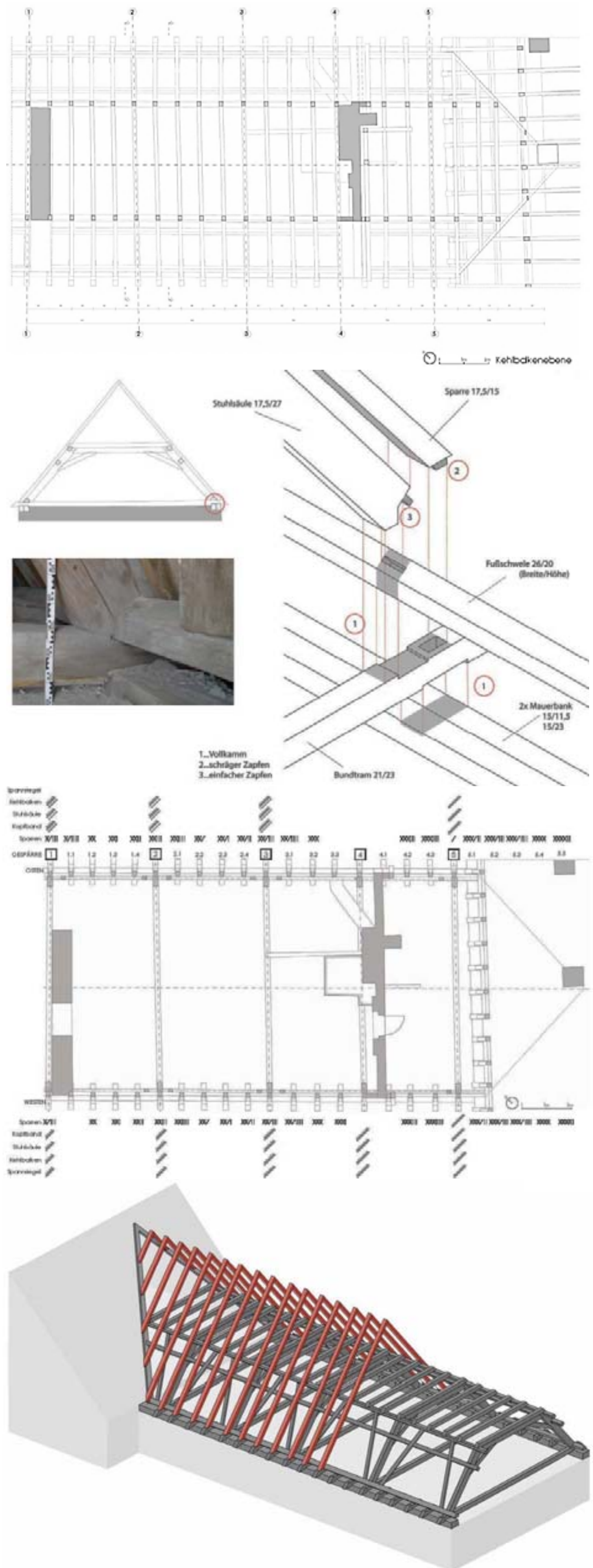

Fig. 1: Results of the architectural analysis of historic roof structures: survey plans, details of joints, carpenter`s marks, hypothesis on the process of assembly (E. G. Gürbüz, V. Hristova, M. Obermoser, A. Seeber; all TU Wien, 2016)

over to structural engineers at *TU Wien Research Unit of Simulation of Materials and Structures* as a sound basis for numerical modelling. (Hochreiner, Eßer, & Styhler-Aydın, 2016) The structural assessment calculation starts with the preparation of a numerical 3D model using the geometrical survey data. These models show both the reconstruction of the initial structural concept of the roof as well as later changes or additions. In this way, the structural situation of different periods can be evaluated. Furthermore, the structural assessment calculation is an appropriate instrument to evaluate intermediate stages of assembly during the construction process (e.g. the hypothesis of the assembly process) and to give hints to temporarily used structural subsystems. The holistic observation, inspection and documentation of the as-built structures, including results from constructional, historical and natural sciences, finally permits the virtual reconstruction of the original structures in 3D CAD models. (Eßer et al., 2016)

In summary, during the analytical process of the current workflow, three different geometrical descriptions of the roof structures are produced: a 3D point cloud, a virtual 3D CAD model and a 3D structural model. All of the models describe the same structure.

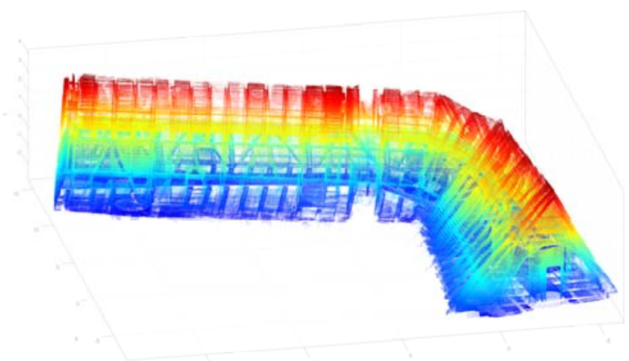

Fig. 2: Roof structure of the Amalienburg in the Vienna Hofburg, 3D point cloud (T. Mitterecker and M. Pöchtrager, TU Wien 2017)

In the scope of research all mentioned data are necessary to analyse and evaluate historic roof structures in the field of construction history. For structural analysis and strengthening measures necessary during the planning of roof extensions and the use of attic lofts, at least the results of a detailed survey including information on the state of preservation have to be provided. In the area of listed buildings even more data from the list above can be required by authorities. In all cases, current labour intensive manual work of 3D documentation and 3D modelling should be replaced by a new approach. The application of an overall, highly automated and time-saving digital workflow for the analysis of historic roof structures is therefore not just limited to scientific purposes and the preservation of cultural heritage but has relevance for planning practice too.

1.2 The Gap: 3D Point Clouds - Architectural Models - Structural Models

An extensive approach to derive volume and mass models of historic roof structures made of timber from 3D point clouds in order to utilize such models in the area of restoration and repair planning processes was developed by the BayFORREST project *Ressourcenschonende Instandsetzung alter Dachtragwerke – Nutzung des Laseraufmaßes und objektorientierter Modellierung*. (Lehrstuhl für Tragwerksplanung, Prof. Dr.-ing. R. Barthel, 2006). The starting point for the volume model was a 3D point cloud, where volume elements of all roof components were modelled in by manual processes. Using computer-controlled component recognition, such volume elements could be transformed into mass elements and linked to internal data bases.

Today, besides the manual extraction of sections for the creation of plan material, 3D point clouds are widely used for the computation of mesh surface representations of cultural heritage objects – like the David statue in Levoy, Pulli, Curless, Rusinkiewicz, Koller, Pereira, Ginzton, Anderson, Davis, Ginsberg, Shade, and Fulk (2000) – for the digital preservation and visualization in virtual reality (VR) and augmented reality (AR). However, less activity occurred in the field of historic timber structures. For an overview also compare Cabaleiro, Hermida, Riveiro, and Caamaño (2017). Still the transfer of the 3D point clouds of roof structures into data that can be used for the analysis of the structure and the construction history is a problem that is not solved yet. More detailed information and geometry of components of reconstructed objects is often not derived. Especially for the structural analysis – e.g. of timber structures – the identification of individual parts and their joints is crucial. Up to now, an appropriate methodology combining the topic-related findings and results in the field of architecture, civil engineering and geodesy is still a desideratum.

As stated in Logothetis, Delinasiou, and Stylianidis (2015) the postprocessing of point clouds to end up with reconstructions of cultural heritage structures in the context of 3D Building Information Modelling (BIM) works still mostly manual, since the automatic feature recognition needs some additional development.

Examples for manual modelling of BIM objects are presented in Karachaliou, Georgiou, Psaltis, and Stylianidis (2019) and Rodríguez-Moreno Reinoso-Gordo, Rivas-López, Gómez-Blanco, Ariza-López, and Ariza-López (2018). The latter article presents an integrated workflow for recording and modelling of historical BIM objects with a laser scanner.

To overcome this labour-intensive step of manual modelling automated methods for object reconstruction are being developed. A first step is to use automated best fitting modelling on (manually) segmented point clouds, where the segments represent individual objects. Modelling the wooden domed structure of the St. Mark's Basilica in Venice was already partially achieved with Leica Cyclone software by Fregonese and Taffurelli (2009). Still, with the manual object separation, large parts of the point cloud processing need to be done manually.

The fully automated and generic modelling of 3D objects with piecewise polygonal planar surfaces at different levels of detail is presented in Nan and Wonka (2017). Their proposed framework of the PolyFit method is implemented in the C++ CGAL library.

Automated modelling of more specific BIM objects is achieved by Ochmann, Vock, Wessel, and Klein (2015) and Thomson and Boehm (2015) with the parametric extraction of walls and rooms. The surface analysis using point cloud and extraction of wall segments provide to handle rooms, corridors and walls as BIM objects. Regarding to their study, more detailed geometric objects such as windows and doors are still not considered.

Wang, Cho, and Kim (2015) proposed a method for automatic building geometry extraction from unorganized point clouds collected from a 3D laser scanner. Aim of the study is to extract exterior walls, foundation walls, windows, doors, roofs and slab components. They provide a comparison between the recognized and the manually measured envelope components for the case study.

A quite different application of the automated object reconstruction was addressed by Xue, Lu, Chen, and Webster (2019) with the modelling of repetitive theatre chairs. Their proposed methodology requires manual definition of the BIM components and their approximate position for the automated modelling process, but it could be applied to a large variety of object types.

While the mentioned publications related to wooden structures either show mostly manual or semi-automated modelling of already object-segmented point clouds, all listed automated methods in the context of Scan2BIM are focusing on quite different topics and are still far off from universal applicability.

Besides the shown developments for parametric modelling of objects from point clouds, there has been significant progress in the field of semantic segmentation on point clouds with deep learning methods in recent years. As shown in Qi, Su, Mo, and Guibas (2017), in this context, neural networks are specifically trained to detect and classify objects of interest in point clouds.

With the new approach – based on the latest development in the automated geometric beam modelling in Pöchtrager et al. (2018) – we want to derive two models from the same point cloud which are therefore "dual" to each other:

a) A structural model: A graph structure is the relevant input for structural analysis, where edges represent rectangular shaped beams and knots represent the connections.
b) The 3D surface model which is relevant for the 3D architectural model. It consists of interlocking beams represented by cuboids or other simplified solids (parametric reconstruction).

While the automated structural modelling is e.g. required for a structural assessment of the roof structure under time pressure, the reconstruction of the geometry in the architectural model can be used to analyze the construction process and historical developments in the construction of roof structures. Missing elements in the graph structure, identified as areas of potential failure or other structural problems, give a hint for a need in refining the model. This opens the path for innovation by integrating data acquisition and modelling. These steps are often considered to be independent from each other.

The overall project work plan envisages the development of a complete and highly automated processing chain from point cloud data acquisition to architectural and structural modelling integrated in BIM.

2. *The approach: Integrated digital workflow for documentation and analysis of historic roof structures, including geometric and structural modelling*

As shown in chapter 1.1, although most of the architectural modelling is still done manually, there are already automated solutions for some applications.

Motivated by already existing approaches in other application areas, the authors are working on a highly automated workflow for the generation of various types of models for the documentation and assessment of historic timber structures.The framework of Building Information Modelling (BIM) provides standards and technologies for the management of different models (object layers), building components and the handling of specific object attributes (e.g. material properties, damage description, age).

The idea is that collaboratively managed models contain information of all research areas involved in the building survey and can be used for interdisciplinary construction analysis. Starting from a 3D point cloud from laser scanning or photogrammetric image matching (Remondino & Rizzi, 2010), the first step in the workflow is the extraction and geometric modelling of all relevant components in the roof construction.

The following subsections present automated strategies for the reconstruction of timber beams and their joints, which is also the current state of development in the project.

The workflow shown in Fig. 3 lists all major processing steps. All python-based automated steps are highlighted with blue color. For the purple colored structural modelling task, Dlubal RSTAB software is used. The methods used could also be extended to other materials and types of framework structures.

The task of collecting and storing reconstructed models and metadata (colored in pink) touches the broad field of BIM and thus can be solved with a variety of available tools like Revit and xBIM (see Antonopoulou & Bryan, 2017). The corresponding sub-section 2.5 shows important data and information to be handled.

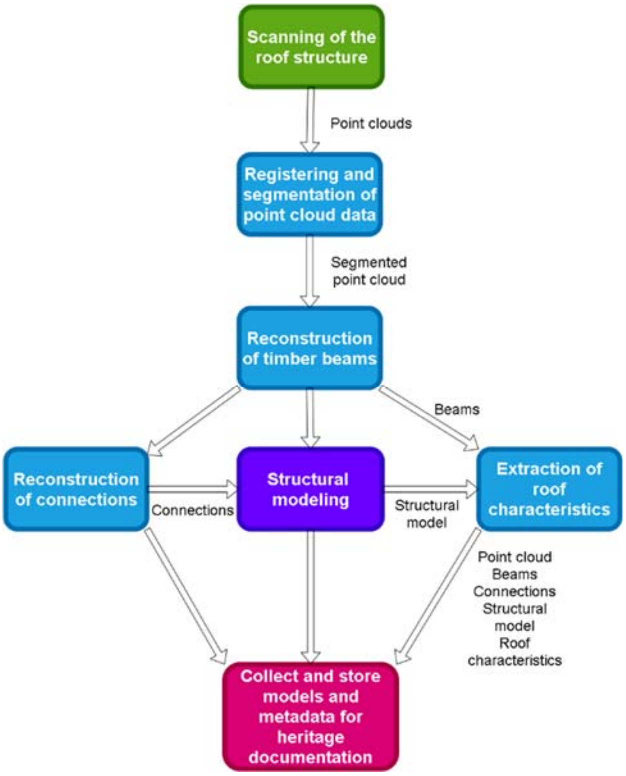

Fig. 3: Main process workflow from point cloud to BIM documentation (T. Özkan, TU Wien 2020)

2.1 Reconstruction of timber beams

The proposed method for the geometric reconstruction of timber beams, as shown in Pöchtrager et al. (2018), consists of the following main processing steps: i) Point cloud segmentation to identify points on planar beam surfaces (beam side faces); ii) Intersection of adjacent beam side faces and compilation into geometric solids that represent the beam – least squares fitting of geometric surfaces of the solid and measured points; iii) Elongation and intersection of modelled beams for model completion. The used workflow is developed for straight beams with rectangular cross-section. It has been tested and validated on dense point clouds from laser scanning, where one can expect an accuracy of better than 1 cm for the reconstruction of beams.

The difficulty in modelling the beams is to support a large variety of different beam cross-sections. While in timber constructions most beam cross-sections have (almost) rectangular or simple polygonal shape, the situation can be much more diverse for other structures, e.g. steel constructions. Fig. 4 shows the current state in the project: reconstructed wooden beams of a roof structure in the Vienna Imperial Palace. While the upper model shows only the central axes of the reconstructed beams, used as one necessary input for the structural model, the representation with cuboids in the lower figure already roughly shows the actual shape of the construction.

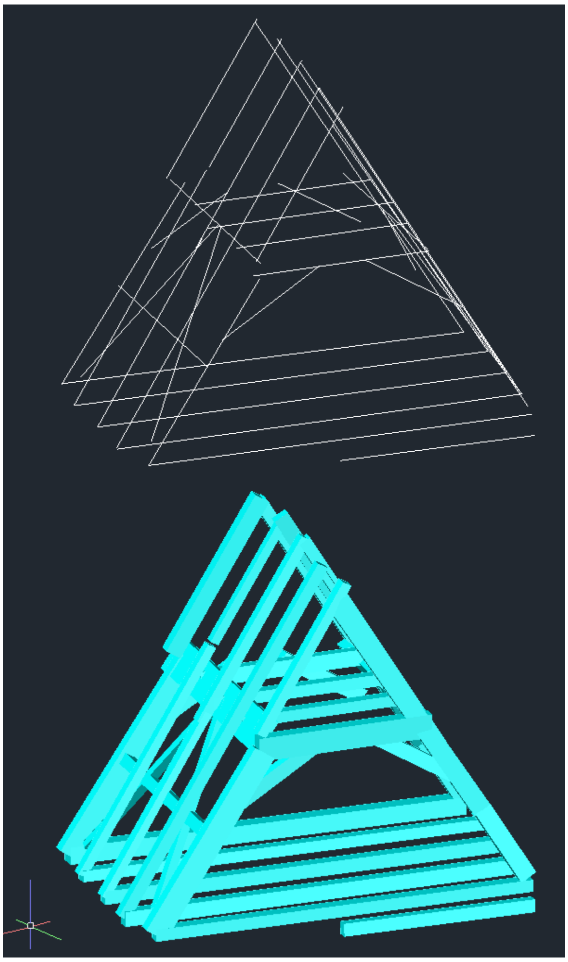

Fig. 4: Reconstructed roof structure of the Amalienburg in the Vienna Hofburg. Top: Central axes of beams. Bottom: cuboid representation (M. Pöchtrager, TU Wien 2018)

Besides the difficulty in modelling arbitrarily shaped cross-sections with straight beam axis, a second challenge is the correct reconstruction of beams with originally intended or later induced curved longitudinal axes. As the wooden beams in Fig. 4 have been modelled with straight longitudinal axes, some elements that have deformed over time could induce systematic errors in the reconstruction due to the need for extended tolerances for data fitting. The same holds for elements that have already been curved in the production. Methods for the automated modelling of curved elements and beams with non-rectangular cross-section are yet to be developed and evaluated. Cabaleiro et al. (2017) demonstrate an algorithm for modelling of curved, deformed and irregular beams.

2.2 Reconstruction of connections

Small metal parts such as bolt, washers or nuts, as well as smoothly interlocking woodworking joints are hardly detectable within 3D point clouds. This makes the correct reconstruction and classification of connections depend on additional knowledge about the involved beams and the overall construction.

A rather simplistic way of detecting and modelling connections is to look for very close positions of beam axis respectively intersection points of beams and take the shortest connecting structural link between the central axes as first representation of the joint reconstruction. Based on the involved beams and the position within the construction, as well as the orientation and length of the structural link, an additional classification in terms of structural behavior can be accomplished.

While the automated identification of the connections and the modelling of their geometry are already achieved in our workflow, one of the main open issues to be handled is the question of the functional characteristic of a connection. This means, we are looking for further indicative criteria, e.g. to check whether the wooden beams and metal components are still interlocking correctly, so that the joint is still capable of taking all the force assigned to it. Additionally, the position of the connecting axis has to be validated for correctness.

2.3 Structural modelling

Together with the completing short structural links, the assembly of reconstructed beam axes of the wooden beams can already be used in a working structural system for further structural assessment (Fig. 5).

The following information concerning the wooden components is necessary:

- Position and length of single beams
- Dimension and orientation of the cross-section along the beam axis with possible torsion along the beam axis due to significant deviation of the fibres
- Assignment of a strength class in terms of a material profile, e.g. according to EN338:2009 for solid timber elements.

As already mentioned in section 2.2 the type of connections in terms of adequate setting of the

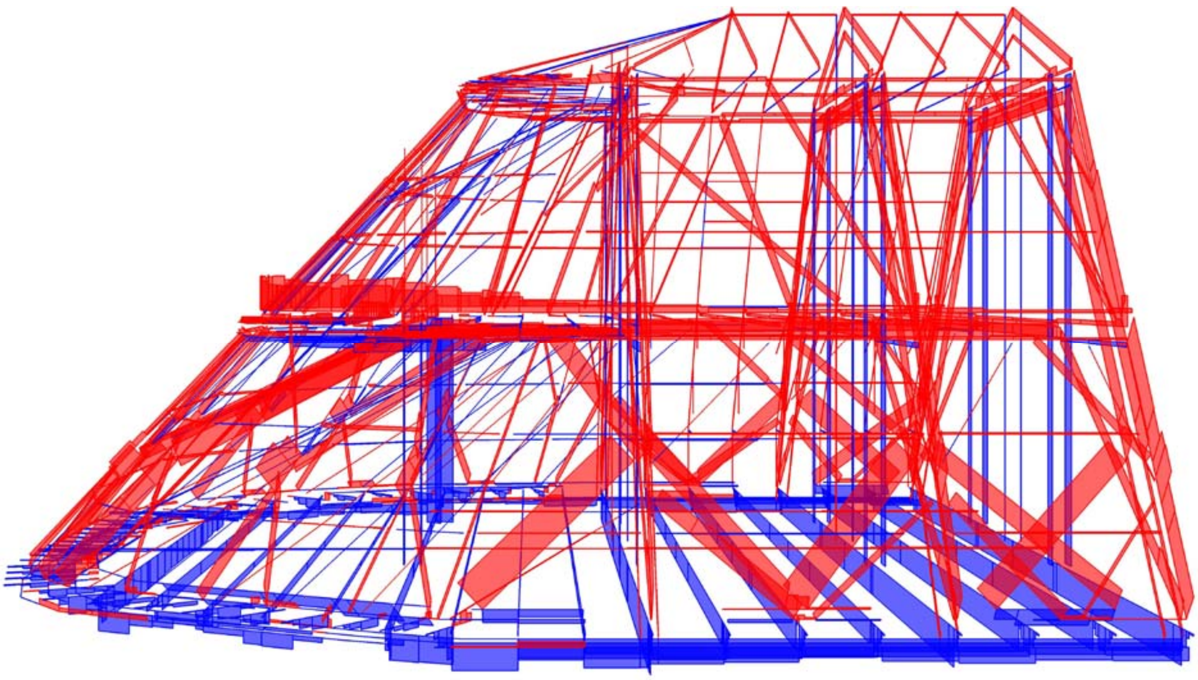

Fig. 5: Distribution of normal forces depending on the structural characteristic of step joints. Roof structure of the Spanish Riding School in the Vienna Hofburg G. Hochreiner, TU Wien 2019

local hinge characteristic is important for the global structural behavior. This means that besides storing the involved beams and the length and orientation of the short linking elements, the corresponding set of internal forces in the joint needs to be identified in line with the structural assessment. While the geometry of connections and the connected beams are already computed within the automated workflow in sections 2.1 and 2.2, information is provided via the BIM data exchange standard of the industry foundation classes (IFC) to carry out the structural analysis in structural engineering software (e.g. Dlubal RSTAB). The written STEP-file for data exchange contains geometry information for beams and connections and material information which has to be assigned to all beams (default: C24 timber). The data transfer has been successfully tested for straight beams with Dlubal RSTAB.

More detailed discussion on the workflow for structural analysis is presented by Pöchtrager, Hochreiner, and Pfeifer (2019).

2.4 Extraction of further characteristics

The automated modelling workflow enables a variety of possibilities for the extraction of further characteristics for roof structures. Based on derived beam dimensions, standard sizes of beams can be determined, and beams of same size can be grouped in a first stage. The information of the position and orientation of a beam within the structure can be used to analyze and classify beams with machine learning with respect to their functionality within the structure. Once this is done, individual beams can be selected as representative to extract architectural respective structural roof characteristics like roof inclinations, span of the roof or the average rafter length or the height of the ridge (Fig. 6).

Additionally, the information about the repetition of similar beams within the roof structure (e.g. same orientation and standard size) can be used to compute characteristics like the rafter spacing and identify irregularities within the construction (see Fig. 7).

The developments in this respect have just started and need to be further evaluated and implemented in the automated processing workflow.

2.5 Storing metadata for heritage documentation

After the successful geometric and structural reconstruction, all modelled and collected information (e.g. from documentation on site, structural evaluation, plans and documents from archives) about the historic roof structure should be stored as tightly linked as possible. The documents collected may include information on

Fig. 6: Derivation of further architectural roof characteristics. Southern wing of the Austrian National Library (M. Pöchtrager, TU Wien 2018)

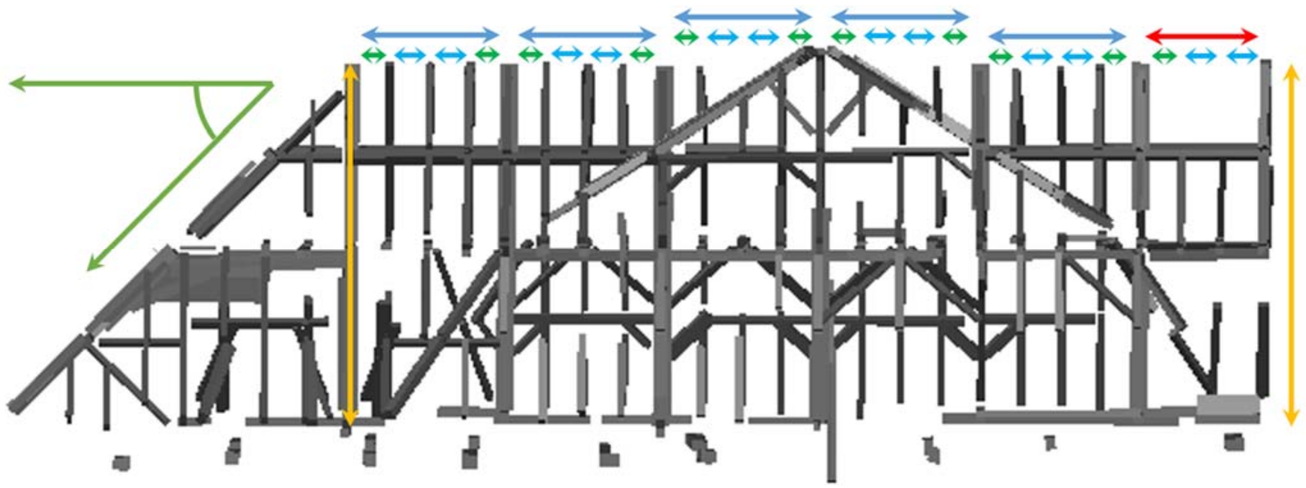

Fig. 7: Regularities in roof constructions. Southern wing of the Austrian National Library (M. Pöchtrager, TU Wien 2018)

the construction process, aspects of local or global damages on the structure and documents for reconstruction and renovation measures. The question of how to deal with the metadata of historic constructions in the context of BIM is addressed by Pocobelli, Boehm, Bryan, Still, and Grau-Bové (2018). In general, BIM allows to store a variety of historic information for various cultural heritage building components and object groups. Some object attributes, to be highlighted for entire historic roof constructions are:

- Information from archival texts (e.g. the age of the construction, name of the carpenter)
- Historical plan material
- Archival photos
- Results of the structural analysis

Specific information for individual wooden components needs to be stored as well. Some examples of attributes could be as following:

- Age of wooden components (as results from dendrochronological analysis)

- Carpenter's marks (with photographs or drawings)
- Detailed modelling of woodworking joints
- Damages (geometric localisation, description and documentation with photos)

In the scope of the presented automated modelling it is important to communicate on which data or method the reconstructed objects are based. In this context, it should be evident which parts of the reconstructed objects were modelled directly from the point cloud and which parts were completed using assumptions in the methodology. Hidden side faces of wooden beams for example can only be assumed, which means we have no direct quality control of those faces within the measured point cloud. Similar holds for the completion of a beam in scan shadow areas. If large parts of an object are therefore reconstructed by methodological assumptions, this information should be stored as metadata on the reconstructed objects.

3. Discussion

Visualisation of objects based on metadata attributes allows more profound analysis and better understanding of the historic structures itself. The new approach provides digital data of the timber structures in formats which can be used easily for the subsequent architectural analysis and structural assessment. Compared to conventional methods, the labour-intensive work of 3D documentation, modelling and analysis of historic roof structures made of timber will be replaced by a time-saving digital workflow enabling straight and stable exchange of data and results between surveyors, architects and structural engineers. Beside the high potential of the research project for further use in Building Information Modelling (BIM), the expected outcome is fundamental for manifold tasks and stakeholders, for instance: calculation and proof of efficient and resource-friendly structural consolidation; adaptive re-use planning for idle attic lofts and the related requirements from building regulations for existing structures; extension of traditional knowledge in the field of construction history concerning carpentry traditions in various periods and scientific classification into the historical development of timber structures.

In order to make the proposed workflow fully applicable in the scope of historic roof structures, minor clarification and improvement are necessary.

At first one would need to integrate quality checks on the laser scanning point cloud. Occluded areas in scan shadows need to be kept at a minimum, as holes in the point cloud will result in missing elements and extended need for assumptions within the reconstructed model. The level of completeness can be checked with a comparison against a manually modelled dataset, but should be at least partially estimated from the acquired point cloud itself. While parameter settings for point cloud segmentation, which are mostly depending on the point density, were not critical (low sensitivity), no additional tests to infer optimal parameters were conducted so far. The segmentation and plane extraction decrease the influence of random measurement errors. Systematic errors, on the other hand, can only be identified by comparison against either a measured point cloud of superior accuracy or a manual model.

A second major question is regarding the generalization within the geometric reconstruction. While at the moment only simple geometric shapes respectively typologies are reconstructed, the modelling of small details is not yet solved. Solutions will be necessary for the modelling of cracks and other damages, as well as details in the wood (e.g. carpenter's marks), woodworking joints or iron components. At the moment all details are stored as metadata on the reconstructed objects and object groups within the BIM.

4. Conclusion

The proposed integrated workflow for the documentation and analysis of historic timber structures shows the opportunities of an automated postprocessing of point clouds into BIM objects in the context of cultural heritage. Although the supported geometry types are still very limited, the article presents a complete processing chain starting from the surveying of the roof to the documentation and storage of historical details. With the large number of measurements in the point cloud we can expect an accuracy of better than 1 cm for the geometric reconstruction of regular objects. Further investigations will be needed to consider the whole construction as a system to go the next step towards an automated extraction of the task within the structural system, as well as the correct detection and interpretation of deformations, damages and missing elements. Regarding data exchange and extended analysis by combining studies in the field of construction history and structural evaluation respective numerical modelling, the presented approach bridges a gap between usually very different kind of information resulting from 3D point clouds, architectural models and structural models. Thus, a sound basis has been developed for enhanced interdisciplinary research on historic roof structures which opens new approaches for cooperation between structural engineering and Bauforschung. In all phases of the analysis it is highly important to store metadata information concerning the reconstruction process and the initial data of the modelling. The main goal in automated reconstruction and documentation of historic roof structures is to keep the entire process transparent, consistent and reproducible.

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