Portico farmhouses of the Vistula Delta: architecture, current state and finite element modelling of timber roof truss under material and cross-section uncertainty

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Abstract: The article focuses on the oldest surviving I-type portico houses located in the Vistula Delta, which were built in the 17th and 18th centuries. The study describes the houses' origins, structure, details of roof structures and technical condition, and it also includes numerical modelling of a roof truss and its mechanical analysis. Numerical models of the roof trusses are defined and analysed by means of the finite element method. Global sensitivity analysis with the use of the polynomial chaos expansion method is used to study the influence of uncertainties in material properties of wood, such as Young's modulus and the friction coefficient, and also the beam cross-sectional height in the output of the numerical model of the structure. The outcomes show that uncertainty of beam height exerts the dominating influence on the maximum deflection of the roof truss hence accurate measurements of geometry are of great importance in the planning of conservation and renovation of such historic structures.

Keywords: architectural heritage, portico houses, timber roof structure, carpentry joints, carpenters' marks, global sensitivity analysis, uncertainty quantification, polynomial chaos expansion, Sobol' indices

1. Introduction

The study concerns portico houses (Germ. Laubenhaus, Vorhallenhaus, Löwinghaus) of the Vistula Delta in northern Poland by the Baltic Sea. These large farmhouses were once landmarks of the delta. The few now remaining are among the last relics of historic wooden architecture in this region (Zybała 2021). The most striking feature of these houses is a gable wall, constituting the facade (or its protruding main section), of which the upper part is supported by the row of pillars, so the composition brings to mind a classical portico (Figure 1). The space between the pillars and the withdrawn wall at ground floor formed in some cases a fairly wide passage enabling a horse and cart to enter and be loaded or unloaded from above.

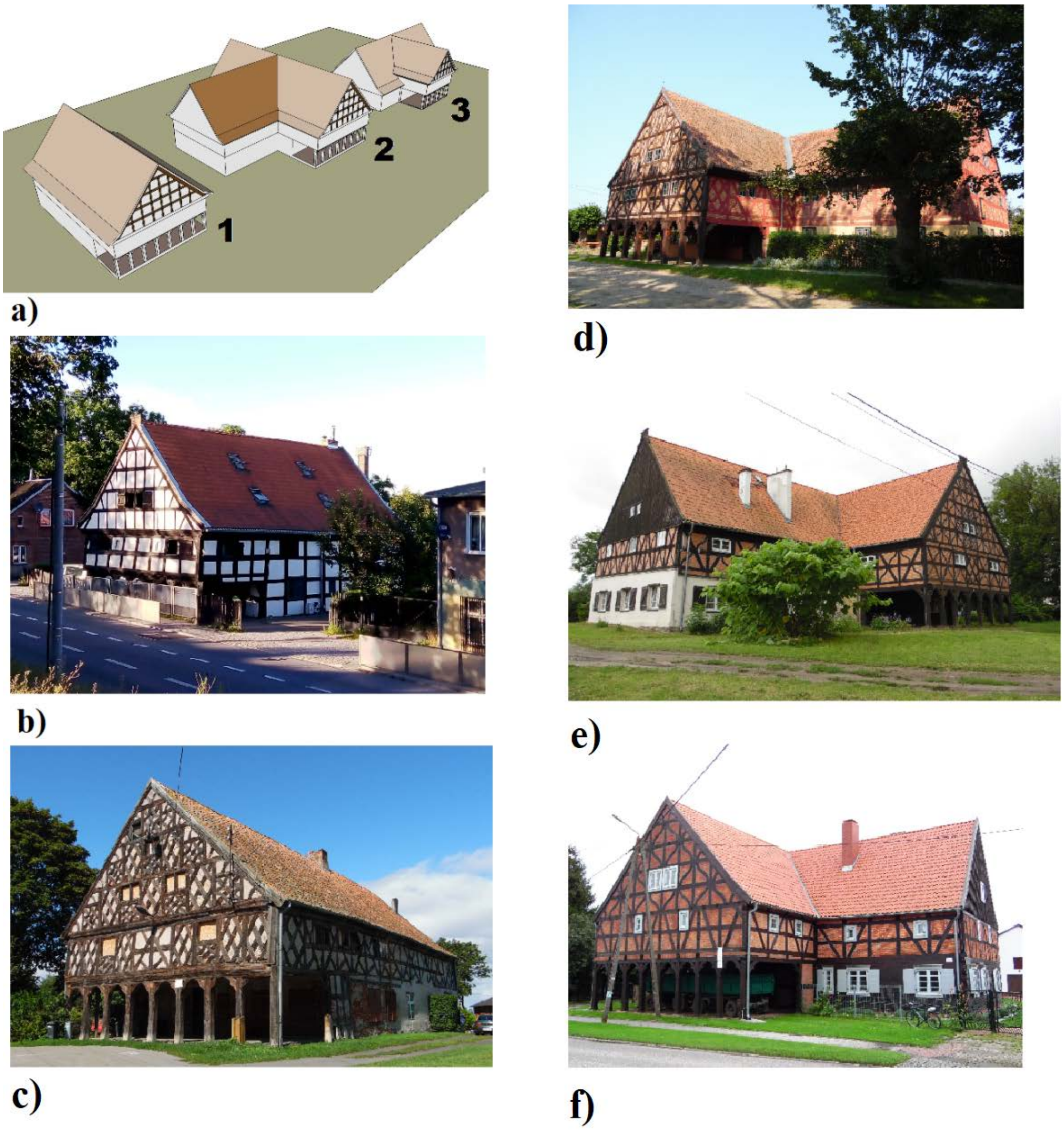

Figure 1. Three types of houses; a) 1, 2 – “I-type” house, 3; The portico houses in: b) Gdańsk Lipce c) Klecie d) Trutnowy e) Miłocin f) Nowa Kościelnica

The portico houses have intrigued architectural researchers as a regional phenomenon for over a hundred years. The oldest publication describing them is the list of monuments from 1884 – 1887 (Heise 1887). The first information on the number and restoration status of the buildings was provided by Bernhard Schmid (1910, 1919) - conservator of the West Prussia province. Subsequently, Otto Kloeppel (1924) published the first study of their architecture. Further research was carried out by Jerzy Stankiewicz (1956) who established the number lost during the war, as well as the number surviving and their technical condition. Newer works (e.g. Domino 2006; Koperska-Kośmicka 2014) have significantly expanded knowledge about currently preserved houses. Most of the houses have not been systematically documented, but the basic, unpublished records from 1950-1988, are stored in the archives of the National Heritage Board of Poland in Gdańsk.

Owing to the crucial role of roofs in protecting buildings against rapid ageing and structural damage, historic roofs are the subject of constant interest from architectural historians, conservation architects and engineers (e.g., Faggiano et al. 2018; Macchioni and Mannucci 2018), but the roofs of the houses in the Vistula Delta have so far escaped their detailed attention. Zybała (2019) undertook a study, the only one of its kind, on the types of roof structures, the size of the cross-sections of particular load-bearing elements, angles of inclination, carpentry joints and the average amount of timber construction of 6 houses from the years 1797-1850. However, there are no exact lists or descriptions specifying the types of roof structures and construction details of the oldest portico houses from the 17th and 18th centuries.

Ageing and loss of the portico houses of the Vistula Delta means that their preservation is increasingly important. However, the proper planning of preservation and conservation of historic structures should nowadays include appropriate modelling and structural analysis (Cruz et al. 2015), carried out using finite element (FE) analysis where appropriate. This provides insight into the mechanical behaviour of the structure, and levels of stresses and deformation and allows the identification of the critical areas and causes of damage (Kujawa et al. 2020). It also helps to predict the post-repair behaviour of the analysed building even when using different or new materials and solutions (Lubowiecka et al. 2019).

Although structural analysis of roof trusses of the houses has not yet been performed or discussed, the general issues of modelling of historic timber roofs have been already widely covered in the literature (see e.g., Parisi and Piazza 2002; Milch et al. 2016; Vannucci 2021; Massafra et al. 2020). For instance, timber roofs have been modelled with various levels of detail and complexity. Armesto et al. (2009) created FE models of a roof truss based on photogrammetric measurements and showed that modelling with the use of beam elements is comparable to a model composed of solid elements but the beam model is much simpler to define and analyse. This type of model is often used in the literature to study the mechanics of timber trusses (Kunecký et al. 2016). A solid model, more complex to define and calculate, allows for more detailed analysis so it is often used to study the local behavior of timber joints (Parisi and Cordié 2010).

Regardless of the approach to the FE modelling, one of the problems in the simulation of historic structures is uncertainty in material properties, geometry, and boundary conditions. The properties of wood as a natural material exhibit high variability. It is also challenging to perform accurate non-invasive measurements on historic monuments. However, the uncertainties can be incorporated into the modelling by using probabilistic methods as proposed by Köhler, Sørensen, and Faber (2007). A reliability-based method was used to analyse an existing historic timber roof by Sousa and Neves

(2018). The uncertainties which are considered in the literature are mainly related to the variability of material properties (Morales-Conde and Machado 2017), decay (Brites et al. 2013), and cross-section (Lourenço et al. 2013). More accurate measurement techniques such as photogrammetry (Armesto et al. 2009), laser scanning (Bertolini Cestari and Marzi 2018) and LiDAR (Hermida et al. 2020) can be used to reduce the uncertainty in the cross-section. Detailed information on the condition of the timber may be also provided by the drilling resistance method presented by Nowak, Jasieńko, and Hamrol-Bielecka (2016). All those methods can be combined to create a predictive model to assess the structural safety of historic timber structures (Cuartero et al. 2019). However detailed measurements are costly and time consuming and therefore are not always used in conservation practice. The decision on further and more detailed studies is often based on preliminary research including basic measurements and structural analysis (Cruz et al. 2015), but the model used to draw initial conclusions already has uncertain parameters. A way to study the importance of those uncertainties is global sensitivity analysis as was employed by Hristov et al. (2017) to quantify the influence of micromechanical properties of wood on its macroscopic properties and by Kłosowski et al. (2018) to examine how uncertainties in material properties and friction affect the behavior of corner log carpentry joints.

The present study focuses on the structural and sensitivity analysis of a roof truss of a historic I-type portico house in the Vistula Delta, shows the method of construction and analyses how uncertain parameters, e.g. material and geometry, typical for old, historic structures, affect the mechanical behavior of the entire roof structure. Two approaches to the finite element modelling method are applied: beam and solid model. In both of these FE models, it is assumed that one of the rafters has uncertain parameters. The decision as to which variables are designated as random in each model is made according to which model parameter is most conveniently varied. For example, in both models the Young's modulus of one rafter is assumed to be uncertain. In the beam model it is easier to reflect the change of the cross-section, which often occurs in degraded historic timber structures. Therefore the beam height is assumed to be a random variable. In turn, the solid model with contact definition allows one to study the influence of uncertainty of the friction coefficient. In both models the Young's modulus of one rafter is assumed to be uncertain.

The methods of uncertainty propagation can be divided in to so-called "intrusive", requiring model code modifications and "non-intrusive", which are based on a series of deterministic calculations (Le Maître and Knio 2010). The latter ones can be easily applied in the case of so-called "black-box" models such as those created in commercial FE systems or for complex nonlinear models, e.g. those including contact. A commercial FE software package is used for the computations in this study so, the non-intrusive probabilistic method is applied. To reduce the computational cost of such analyses, the polynomial chaos expansion in the regression-based variant was applied to perform uncertainty quantification and calculation of Sobol' indices (Sudret 2008). Such a methodology can be applied in efficient planning of conservation and rehabilitation of different types of historic structures especially when only non-invasive material testing is available.

To sum up, the article aims to fill the gap in research on the oldest timber roof trusses of portico houses of the I-type in the Vistula Delta. The study will show which parameters of the mathematical models of the timber roof should be most accurately determined in order to effectively plan conservation works for the future. The study begins with the history of the region in Section 2. Then the construction of the portico houses is presented in Section 3, which also describes the current condition of the houses and presents the results of the survey. Section 4 presents the timber roof FE models, uncertainty quantification and sensitivity analysis framework and results. Finally, everything is summarized and concluded in Section 5.

2. Historical background. The region and people of the Vistula Delta-Żuławy

The Vistula Delta, called in Polish - Żuławy, and in German Weichselwerder, is a large alluvial plain of approx. 2460 km2 (Kondracki 2002), located southeast of Gdańsk (Germ. Danzig), on the periphery of the Eastern Pomerania.

At the beginning of the fourteenth century the Eastern Pomerania, a dominion of the Polish Kingdom, bordered Prussia which was then gradually conquered by the Teutonic Knights, who in 1308 seized Gdańsk and the entire region. In 1466 Poland regained the Eastern Pomerania and kept it until 1772. In 1773-1918 the Delta belonged to the Kingdom of Prussia and then to the German Empire, as a part of the Province West Prussia. In 1920-1939 the area of the Delta was mostly within the borders of the Free City of Danzig, and thereafter in the Third Reich. The territory of the Eastern Pomerania has returned to Poland in 1945.

The development of the Delta wetlands into a flourishing farmland started in the fourteenth century, thanks to settlers from Friesland (Augustowski 1976) and the immigration of Dutch Mennonites' in the sixteenth century (Klassen 2009). Natural and human activity made the Delta's landscape similar to the Dutch marshland (polders) (Bertram, Kloeppel, and La Baume 1924) with networks of canals, flood embankments and ditches. That landscape of the Delta was devastated in the heat of the German-Soviet struggle in 1945. The indigenous population fled before the forthcoming Red Army; the remaining those who stayed were deported thereafter.

The attitude of Poles towards the cultural heritage of former Royal Prussia (as the Eastern Pomerania was called under Polish rule (Friedrich 2000) was complicated. The population of the Delta was mixed: some had old roots from the pre-Teutonic period (Prussian, Slavic - Polish), some were descendants of German or Dutch colonists. The same can be said about their religion: there were Catholics, Lutherans and Mennonites (Friedrich 2000). The influx of German people and the national policy of the Prussian State turned that mosaic into unified society, firmly identified with Germany (Belzyt 1998; Bockmann 1992; Neumeyer 1993; Gałka 2017).

After 1945 Eastern Pomerania was perceived by Poles as once again regained part of Poland. Homeless Polish newcomers, whom the fate brought here, chaotically settling in abandoned, sometimes semi-ruined towns and villages were trying to reconstruct their existence in postwar confusion, uncertainty and poverty, in overcrowded houses, and the next decades of life in economically inefficient system of "real socialism". All that create a generally unfavourable atmosphere for "Prussian" architectural heritage to care (Glendinning 2013). Most of the portico houses fell victim to it.

However, Gdańsk, the never forgotten "jewel" in the Polish Crown, was rebuilt after 1945 as a symbol of the Polish return to Pomerania (Kalinowski 2005).

3. Structure of the portico houses

3.1 ***The portico houses.***

Kloeppel (1924) differentiated three basic types of houses, (Figure 1a). It should be noted that the term *portico* should be treated somewhat conventionally here, and in some cases, the term *arcade* might be substantiated. In the building of the first and second type, the portico constituted the facade of the house, so we can call them I-type houses. The second type was in fact a result of the development of the I-type plan by adding a wing to the body of the house. Therefore, for this study they can also be classified as belonging to the same I-type. The houses of the third group were different; the portico was situated in the middle of the longer wall of the body. Their layout differs significantly from previous types, so they will not be the subject of this study.

The total number of the portico houses in the Delta is unknown; in the mid-1950s there were around 130 houses (Stankiewicz 1956); the number of I-type houses was only 12. Currently, according to the National Inventory of Historical Monuments (The National Inventory of Historical Monuments 2020), only about 50 homes have survived in a different state of preservation – both well-maintained and partially ruined.

The oldest preserved house in Lipce by Gdańsk (Germ. Guteherberge) was built ca 1600 (Kloeppel 1924 ; Bertram, Kloeppel, and La Baume 1924), (Figure 1b). The newest houses, retaining traditional style and proportions, come from the 1840 (Woede 1980).

Unfortunately, only 5 I-type houses have survived until now: in Lipce, Trutnowy (Germ. Trutenau, 1720), Miłocin (Germ. Herzberg, 1731), Klecie (Germ. Klettendorf, 1750), Nowa Kościelnica (Germ. Neumünsterberg, 1750). The house in Lipce is the last representative of the once most widespread pure I-type.

Porticos or porches are elements well known in European architecture, and almost the same buildings can be found not only in other parts of East Pomerania or in the neighbouring East Prussia, but also remote western subregions of Pomerania, western Greater Poland and in Brandenburg (Schmid 1938). Moreover, various types of wooden buildings looking alike were also common in the folk architecture of Poland or Lithuania (Schmid 1910; Kulke 1939; Prokopek 1976; Tłoczek 1980).

Remarkably, the half-timbered houses with wooden "arcades" on the ground floor, quite similar to the pure I-type homes were built not only in the villages or suburban areas. They could form most of the early urban fabric in numerous towns with German town law, founded in the 13th c. in Lower Silesia, and perhaps in many new towns founded at that time in other regions of Poland. They, unfortunately, disappeared from the townscape over time, replaced with brick buildings, but their forms are known from reliable iconographic sources (Wernher 1800) (Figure 2c) (Kulke 1939). Similar houses were certainly also built in the newly founded towns in the state of the Teutonic Knights in the middle ages, and later, until the mid-18th century. The rare example of such an I-type portico house survived until 1945 in Friedland by Königsberg (Rus. Pravdinsk, by Kaliningrad, Russia) (Figure 2d). Although non-existing now, it was well documented (Dethlefsen 1918; Witt 1932) and can be credible testimony to the presence of such houses in East Prussia. Even though it was built only after the great fire of the town in 1553, the patterns for this, and other similar buildings were older. It is not known whether, or what I-type houses were built in small towns in the Delta. Apart from the house in Lipce, the only similar building from 1771, (former smithy) survived in the Gdańsk suburb Stare Szkoty (Germ. Alt Schottland = Old Scotland); however, it is small and difficult to compare with big buildings in the Delta.

3.2 ***Structure of the I-type house.***

The choice of a type of house (as well as a wealth of its decorations, e.g. rococo or neoclassical) were presumably results of the economic status of the owners and skills of local, mostly anonymous master builders.

Due to the small numbers of I-type houses preserved, it is difficult to find reliable genetic or developmental regularities of their structures. The bodies of the houses were founded on rectangular plans (Figure 3).The width of the body is usually around 11.0 m; also the width of the wings is similar or 10.0-11.0 m. The total length of the houses is between 19.0 and 26.0 m. The least complicated is the house in Lipce (approx.11.0 x 19.0 m), and it is the only existing example of the pure I-type house - very popular in the Vistula Delta in the 17th or 18th c. Interestingly, the dimensions of two, very similar houses in Lüdersdorf in Brandenburg are almost the same: 11.5-12.0 x 20.0 m; (Kulke 1939), (Figure2b). However, the relatively late (1750) house in Klecie (Figure 3) has a body width of approx. 13.00 m.

The space of the body of the house has been divided lengthwise into two sections. One is a two-story hall, in which - in older homes (Germ. Dielenhaus, Hallenhaus (Woede 1980), such as the house in Lipce - a large kitchen hearth was situated (Figure 2d, 3), as well as the wooden stairs leading to the gallery on the first floor. This high hall is an interesting feature of the I-type houses in the Delta; the houses in other regions seemed not to have similar rooms. In newer, bigger houses this scheme was somewhat transformed: instead of hearths, there were central, “dark” or “Polish” kitchens without windows (Kloeppel 1924) (Klecie, Miłocin, Trutnowy, Nowa Kościelnica) (Figure 3). The galleries on the first floor encircled the hall; the ladder stairs were replaced with comfortable staircases. The other section is divided into smaller rooms. The first floor is similarly divided but there is also a room above the open space of the portico. In the big houses with a wing (e.g. Miłocin, Trutnowy), the rear part of the house was separated from the hall by a wall. The attics served commonly as granaries.

Interestingly, a similar, bipartite structure, with partially two-story halls had the half-timbered houses in Friedland (see e.g. the portico house Markt 16, (Figure 2d). It is worth noting that the high hall (Germ. Hohe Diele) was a typical part of the structure of the medieval burgher houses in northern Europe, from the Netherlands to Livonia. Those houses were not as wide as free-standing farmhouses and they were only two Culmish rods in width (- Alt-kulmische Ruten, ca 8.5-9.0 m), which was typical for urban plots in Prussia. The resemblances of the oldest and simplest I-type farmhouses to half-timbered Prussian burgher-houses may suggest, that these last were models for the homes in the Delta. Other possible links between the Delta portico houses and half-timbered architecture of northern Germany, or with the forgotten traditions of local, old-Prussian, Slav (or latter Polish) constructions are disputable and will probably never be explained due to lack of material evidence.

The portico houses were originally half-timbered or entirely timbered; also combinations of both techniques were frequently applied; (sometimes timber walls were partially replaced with bricken ones. However, all the survived I-type houses are half-timbered structures.

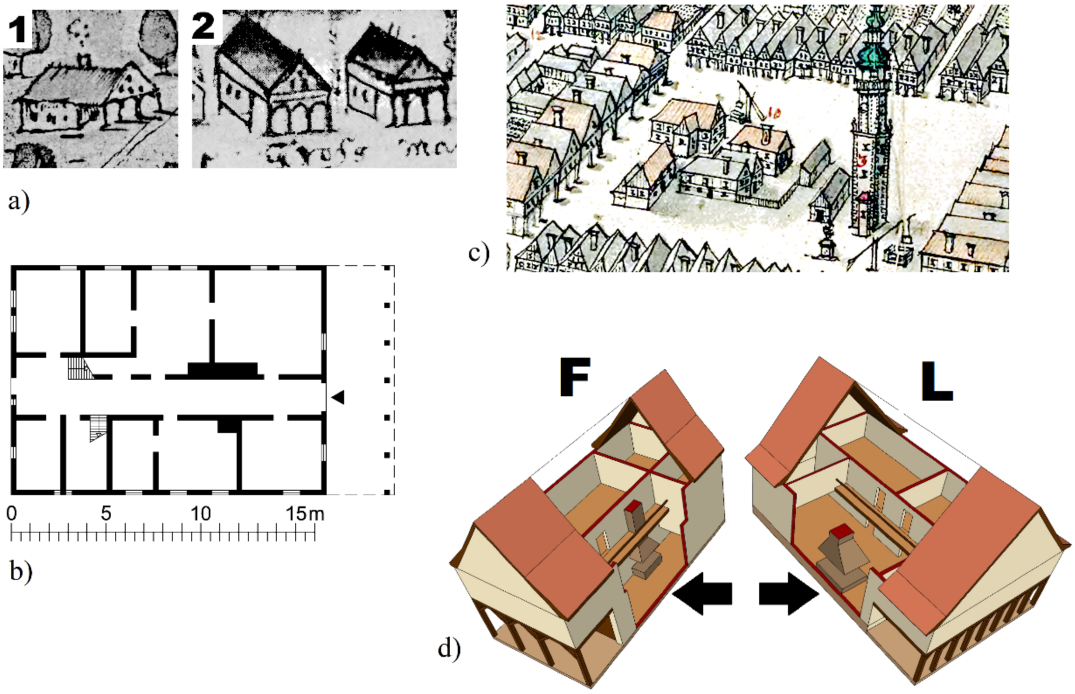

Figure 2. a) I-type houses: 1 – a one-story house by Gdańsk, ca 1650 (detail of unidentified plan from authors' collection); 2 – two story houses in Myszewo (Germ. Mausdorf), 1647 (Kloeppel, 1924). b) Lűdersdorf, Stegmann's House, plan (after Kulke 1939). The three-section structure of the interior is visible. c) Kąty Wrocławskie (Canth), Lower Silesia, detail. Half-timbered and wooden burgher houses (Wernher, Pars IV, ca 1750). d) Comparison of analogous house structures: F – Friedland, house Markt 16 (after Witt 1932); L – Lipce by Gdańsk. The arrows point to high halls with open hearths.

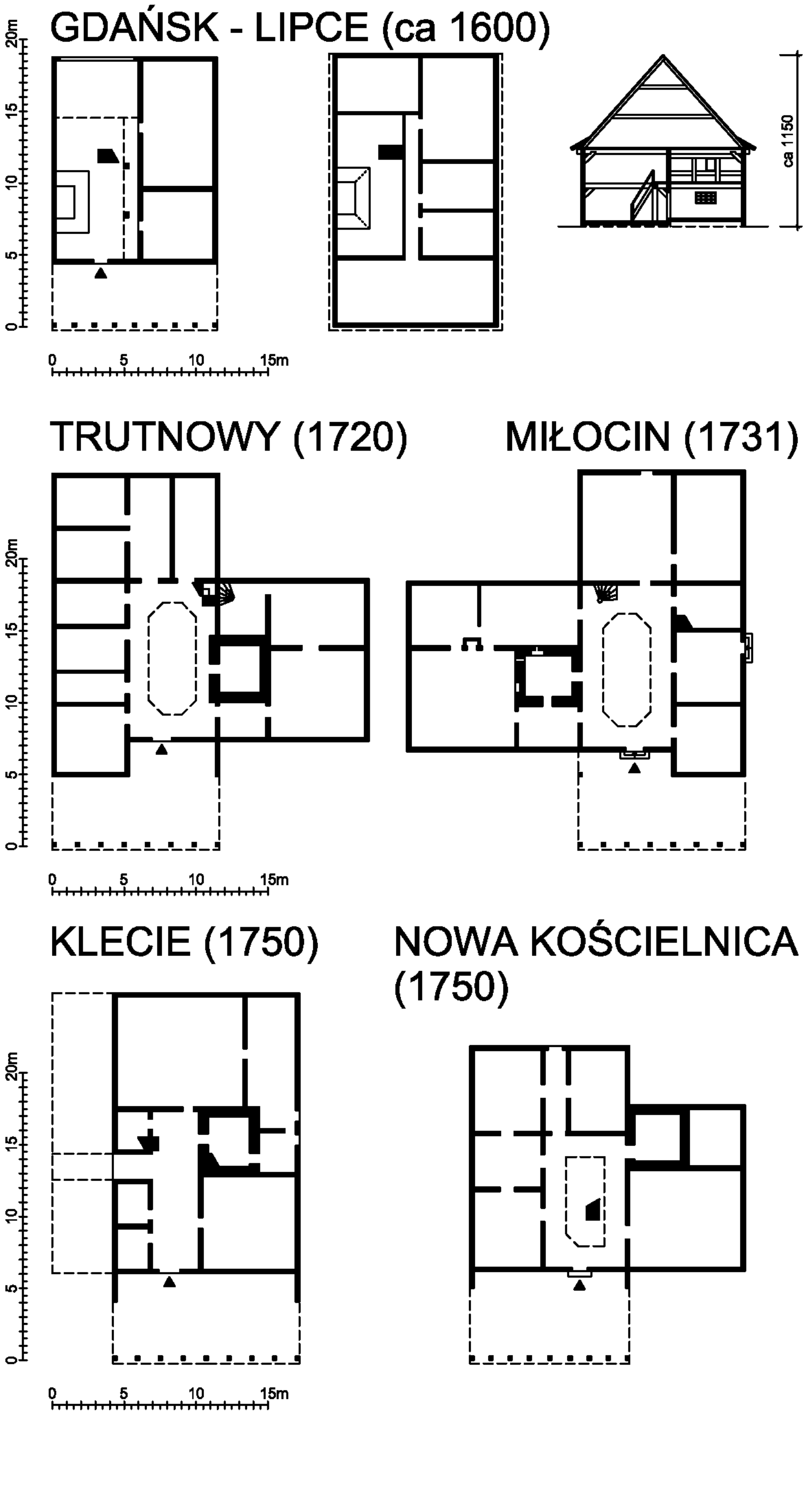

Figure 3. Plans of portico houses; Lipce, Miłocin, Nowa Kościelnica - reconstructions of the original plans after Kloeppel (Kloeppel 1924); Klecie - reconstruction of the original plan after Schmid (Schmid 1919) and Trutnowy.

The foundations - basically built of field stones - were shallow (approx. 0.40-0.80 m below the ground surface) due to the high level of groundwater. For the same reason the houses had only small, barrel-vaulted, bricken cellars. The portico pillars were situated on individual foots (sometimes on padstones - e. g. Miłocin) or on one beam (e. g. Lipce, cross section 0.25 x 0.29 m) laid on stone foundation.

The half-timbered construction represented Low German type (Woede 1980). The exemplary dimensions (Lipce) of the cross-section of beams were (height x width): sills (0.25 x 0.29 m), plates and girts (0.25-0.28 x 0.25-0.31 m); posts (0.25-0.31 x 0.26-0.28 m); pillars of the portico (0.26-0.30 x 0.30 m). The infill of walls was nogging or wickwork and clay. Ceilings were constructed with beams (0.28-0.32 x 0.24-0.26 m), with a spacing of approx. 1.00-1.40 m. The I-type houses were covered with large steep gable roofs. The roofs of the described houses were - covered with tiles; cheaper houses were also commonly thatched. The gable roof of very simple structure was the most characteristic type in the region of the Delta regardless of the location – in a town or countryside; or dimension of a building. More complex, half hipped with gablet or hipped were also used but later, and they were rather rare (frequently covered only a part of a building).All the I-type houses have two floors. Though the two-story houses were popular in the Delta region, the most common were certainly one-story portico houses (Figure 2a), built also elsewhere. Examples of similar, two-story homes, have also been preserved in Brandenburg, e. g. in Garz, Staffelde or Lüdersdorf (Kulke 1939). However, they were presumably also less common than one-story portico houses in that region.

3.3 ***Case study. Analysis of historic houses.***

The oldest (built in 1600-1750), preserved I-type houses from the Vistula Delta area were selected for field research. All analysed buildings are listed in (The National Inventory of Historical Monuments 2020). Field test was performed in five houses: Lipce by Gdańsk (Germ. Guteherberge) (Figure 1b), Klecie (Germ. Klettendorf) (Figure 1c), Trutnowy (Germ. Trutenau) (Figure 1d), Miłocin (Germ. Herzberg) (Figure 1e), Nowa Kościelnica (Germ. Neumünsterberg) (Figure 1f).

The state of preservation of portico houses and their roof structures was assessed on the basis of *a desk survey* and *a measured survey* following (Cruz et al. 2015). The analysis of historical and conservation documentation from the following archival sources was made: The National Heritage Board of Poland in Gdańsk, Provincial Office of Monument Preservation in Gdańsk, Polish Academy of Sciences library in Gdańsk and Gdańsk University of Technology library - historical section. The purpose of the query was to find information about the history and renovation of individual houses in: Gdańsk (Rosowski and Szczęsny 1957; Krzyżanowski 1960; Szulc 1957), Trutnowy (Lewandowski 1978; Cinkusz 1984), Miłocin (Cinkusz 1983; Kożuch 1959), (Tomaszek 1959), Klecie (Orzechowska 1959; Milkiewicz 1995) and Nowa Kościelnica (Chruszczyńska and Przytocka 1995). The results of the archival query are shown in Table 1 and Table 2.

During visual inspections in the years 2017-2020 the construction of houses was examined (foundations, walls, ceilings, roofs), decorative inscriptions and carpenters' marks (Figure 4). Results of field research are shown in Table 1 and Table 2. The cross-sections of the construction elements, the span of the roof structure, the number of particular elements, the angle of inclination were measured (Figure 5), see e.g. (Sousa et al. 2016). The types of carpentry joints were determined (Figure 6), photographic documentation showing the current condition of roof construction was made (Figure 7). To compare different types of roof structures the amount of timber used for their construction was calculated (Bláha, Kloiber, and Serafini 2018). To compare the amount of timber in the roofs of investigated houses, a measure following Kapuściński (2012) is used:

$$\overline{V} = \frac{V}{RL}, \qquad (1)$$

where:

V – the volume of the structural elements of one truss;

R – average spacing of trusses;

L– truss span.

The calculations include the main construction elements of the roof structure (collar beams, rafters, posts). Tie beams were not taken into account and their cross-sections were not measured because they are covered with the floor and ceiling structure. Wind beams, purlins and other elements used to fasten the roofing were also omitted in the calculations. They are often replaced during roof renovation and are not the main construction elements.

3.4 ***Results***

It was shown that the most frequently used construction solution for the roofs amongst investigated houses from the 17th-18th century is a collar beam type. In houses in Miłocin, Nowa Kościelnica, and Trutnowy, there is one collar beam, and in houses in Klecie and Gdańsk, two collar beams. It is worth adding that in the house in Gdańsk there are additional elements supporting the lower collar beam - two posts. It is interesting that such a simple roof trusses were used to cover buildings of a significant widths, reaching approx. 13.00 m.

Structural elements have carpenters' marks, mainly with Roman numerals, designating to be attached rafters and collar beams. They show that these elements are made from traditional carpentry techniques and confirms that the roof structures are authentic. Detailed information is provided in Table 2.

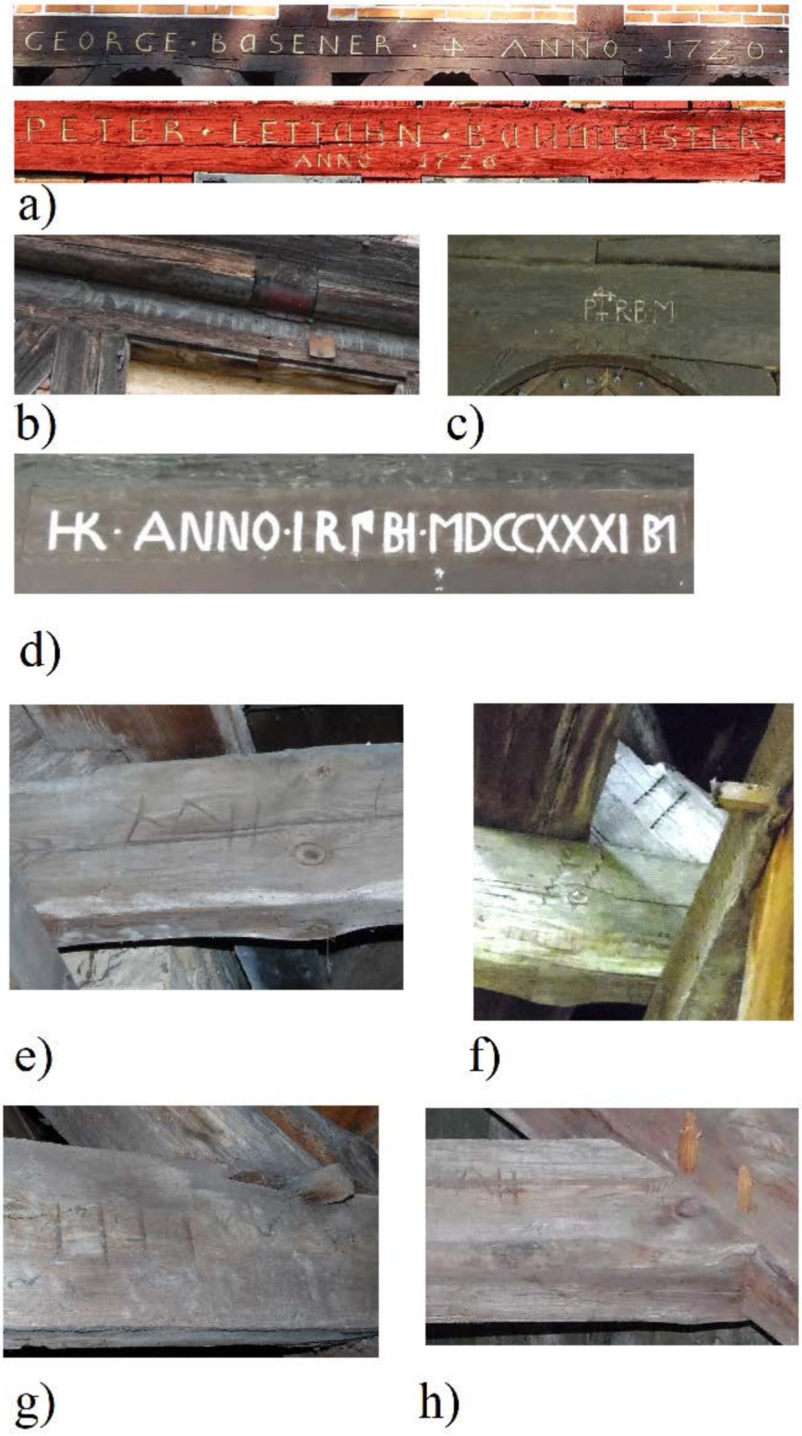

Figure 4. Inscriptions on houses: a) Trutnowy b) Klecie c) Nowa Kościelnica d) Miłocin Carpenters’ marks on roof truss elements: e) Trutnowy f) Trutnowy g) Klecie h) Nowa Kościelnica.

Table 1. Results of archival query and field research - construction of portico houses

no	1	2	3	4	5
location	Gdańsk	Trutnowy	Miłocin	Klecie	Nowa Kościelnica
date of construction	1600	1720	1731	1750	1750
house builder	unknown	Peter Lettahn	only the initials of the house builder - *IR* are known	unknown	only the initials are known *PR*
primary function	on the ground floor, on the first floor there was an apartment for the owner, and there was a granary for grain above the arcade	residential building and grain storage	residental building	there were living and farm rooms on the ground floor, bedrooms on the first floor, and a granary for grain on the upper level of the portico	like other houses in the past and nowadays, it has residential and storage functions.
current function	hostel	residential building, arts gallery	multi-family house	house is inhabited and there is also a meeting room for the villagers on the ground floor	
renovations of houses	1930, 1960, 2003	1930s,1958,1980,2014	19th, 1928, 1978-1982, 2010-2011	19th, 1929, 1935, 1959	1968, 2013-2014
			Construction of houses		
foundations	made of stone	made of bricks	made of stones and bricks	made of stones and bricks	made of stones and bricks
walls	the walls of the ground floor and the first floor have a half-timbered construction (germ. *Fachwerk*)	walls of the ground floor are constructed of bricks, the walls of the first floor are half-timbered construction filled with bricks	walls of the ground floor are constructed of bricks, the walls of the first floor are half-timbered construction filled with bricks	walls of the ground floor are constructed of bricks, the walls of the first floor are half-timbered construction filled with bricks	walls of the ground floor are partly constructed of brick (main wing) and timber log walls (side wing). The walls of the first floor are half-timbered construction filled with bricks
number of columns in portico	9	8	8	9	9
ceilings	made of timber beams	made of timber beams	made of timber beams	made of timber beams	made of timber beams
decorative inscriptions (Figure 4)	no incriptions	there are two decorative inscriptions: the first above the portico with name and surname of the first owner ,,*George Basener* " and date of construction of the house *„Anno 1720 den 15 Augustus"* , the second incription placed on south gable wall with name and surname of the house builder and the date*,,Peter Lettahn Baumeister Anno 1726"*	there is only one inscription above the main entrance to the house "*HK ANNO IR (sign) BH MDCCXXXI BM* " ; "*HK* " is an initial of the first owner, ,,*ANNO* '' menas a year, "*IR* " is an initial of the builder, next is a sign, followed by the whole letter B and half of the letter H ,,BH''- which is an abbreviation of the word - *Bauher* (German) - owner, next is a year of house construction ,,*MDCCXXXI* " and the whole letter B and half of the letter M ,,*BM* ", which is an abbreviation of the word *Baumeister* (German) - builder	one sentence is placed on the beam above columns, written in German, with information about the first owner along with a blessing: *„Dawid Zimmermann hat bauen lassen dieses Haus Gottsegne die da gehenein und aus hat ernichtgebautnach seines nachfartssinn so bauersicheinbessereshin"*	there is only one inscription above main entrance to the house with initial of house builder ,,*PR";* next ,,*BM* " which means *Baumeister* (German) - builder
remarks	despite the building of additional internal walls in 2003 and the cladding of the roof structure by plasterboards sheets, the original structure of the building has not been changed	-	the portico house in Miłocin was built for Heinrichs family	the portico house in Klecie was built for Dawid Zimmermann, which is confirmed by decorative inscription	-

Table 2. Results of archival query and field research - roof constructions

no	1	2	3	4	5
location	Gdańsk	Trutnowy	Miłocin	Klecie	Nowa Kościelnica
type of rafter truss	the collar-beam type (with two collar beams and posts)	collar beam type	collar beam type	collar-beam type (with two collar beams)	collar-beam type
carpentry joint in the ridge	roof structure is covered by plasterboards since 2003	lap joint	new roof construction was made in 2010-2011	lap joint	lap joint
carpentry joint: rafter and collar beams	not visible	dovetail notch	not visible	dovetail notch	mortise and tenon
roof covering	red pantiles	red pantiles	red pantiles	red pantiles	red pantiles
renovations of the attic	2003	1980	2010-2011	-	2013-2014
technical condition	good, roof covering is raintight, no additional loads	good, roof covering is raintight, construction elements do not show significant damage and deflections no additional loads	good, roof covering is raintight, construction elements do not show significant damage and deflections, no additional loads	good, roof covering is raintight, construction elements do not show significant damage and deflections, no additional loads	good, roof covering is raintight, construction elements do not show significant damage and deflections, no additional loads
gravity ventilation of the attic	intact	intact	intact	intact	intact
carpenters' marks (Figure 4)	no data available because of plasterboards covering the roof structure	two types of carpentry marks are visible on the roof constructions: Roman numerals, for instance XIII, XVIII or IIIIIIII made by broad axe and marks' consisting of small triangles which create shape II made by chisel or gouge	no carpenters' marks because the roof construction is made of new timber (100%), without reuse of previous historical elements	the Roman numerals are visible on the rafters, for instance: IIII, V, VII, X	carpenters' marks are visible on old elements which were reused in roof modernization in 2014, for instance V, VII, VIII
remarks:	Geometry and dimensions of historical construction elements have been described in conservation documentation (sections and plans)	The roof structure was originally collar beam type. In the years 1978-1982, additional construction elements (purlins, posts, braces) were added to strengthen the entire roof structure.	In 2010-2011, the structure of the roof truss was completely replaced with a new one due to its bad technical condition. At that time, the attic was turned into an exhibition and conference room. Geometry and dimensions of historical elements have been desribed in conservation documentation	-	In 2013-2014 (house renovation), many load-bearing elements of the roof structure were replaced, because of bad condition. During the work, efforts were made to keep as much of the original structure as possible, hence many combinations of old wooden elements with new ones.In the attic, after the completion of construction works, the old crane for pulling grain sacks was installed in the same place.
			Details of roof construction		
wing width (m)	11.0	11.2	11.3	12.3	11.0
rafter (cm)	18x20	21x25	20x24	20x25	19x24
bottom collar beam (cm)	16x18	-	-	14x24	-
upper collar beam (cm)	16x16	14x22	12x20	14x24	16x19
m)	11x17	-	-	-	-
span of n)	1.40	1.20	1.46	1.30	1.30
of trusses	12	19	17	17	16
)	49	47	47	47	46
n^2)	0.066	0.078	0.056	0.086	0.060

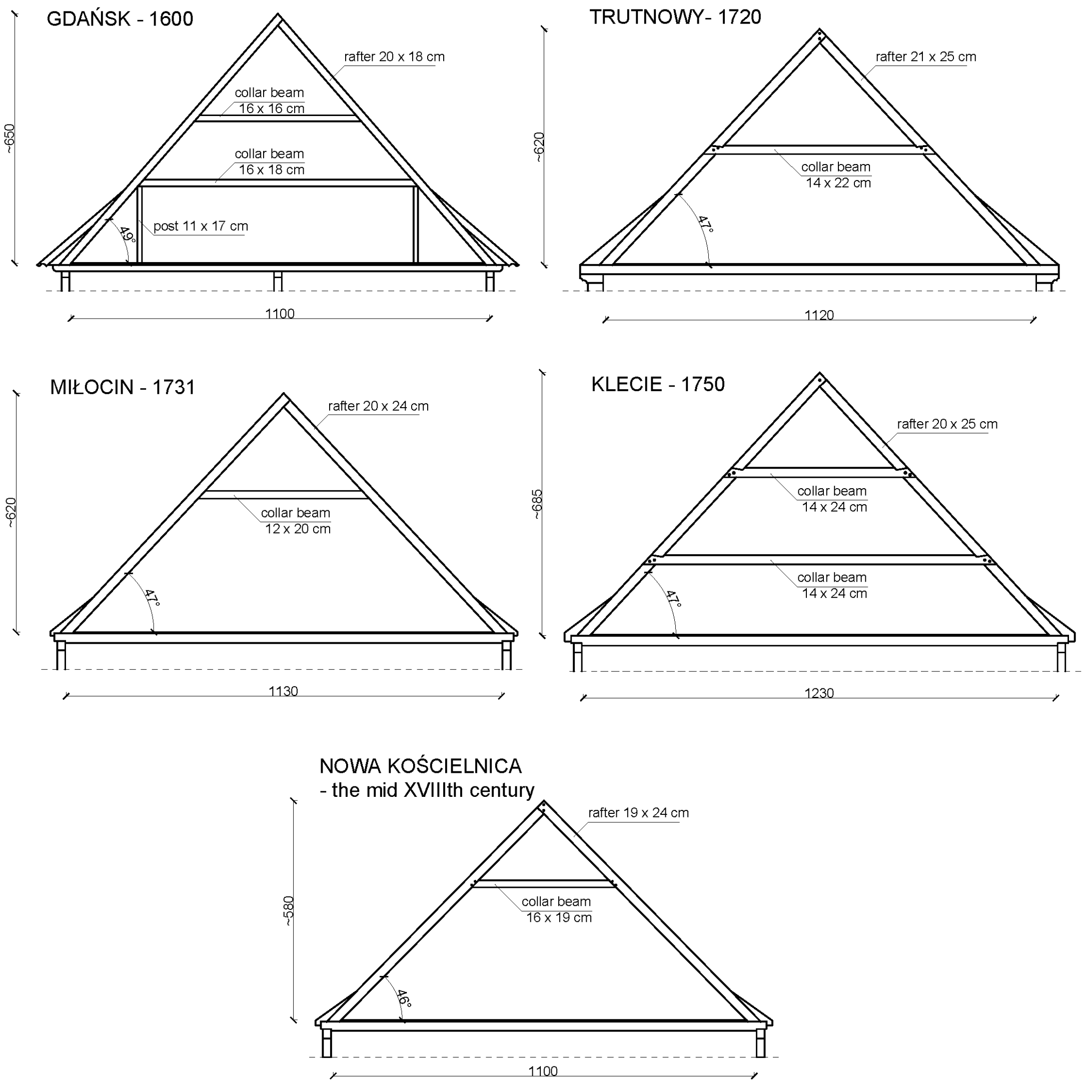

Figure 5. Timber roof truss schemes (Gdańsk, Trutnowy, Miłocin, Klecie, Nowa Kościelnica)

The houses in Trutnowy, Klecie, Miłocin and Nowa Kościelnica have decorative inscriptions, showing names and surnames or initials of their owners and builders. This is an example of a common local tradition commissioned by wealthy proprietors. These decorative inscriptions distinguish these houses from the others in the Vistula Delta. Detailed information is provided in Table 1.

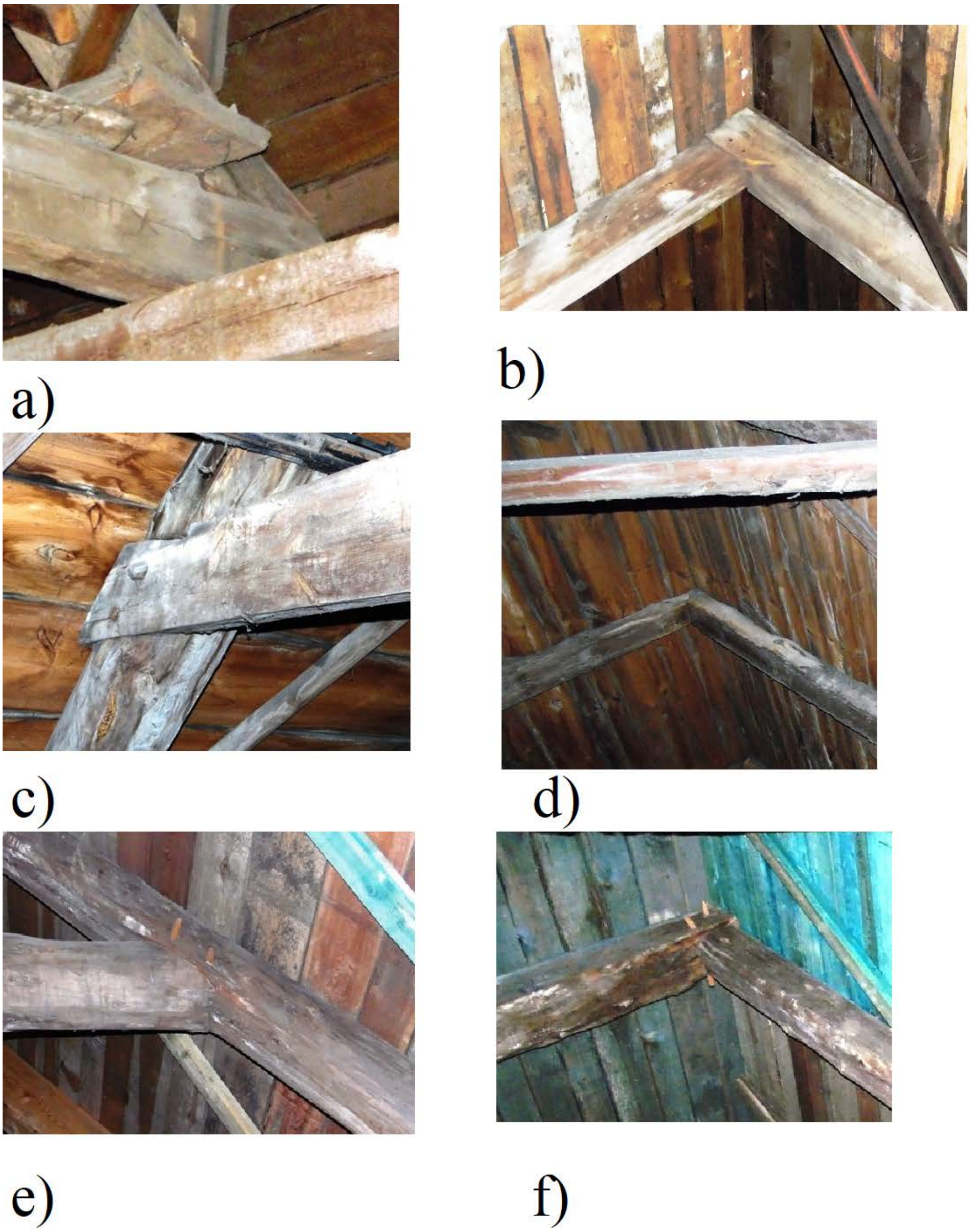

Figure 6. Traditional carpentry joints - current state: a) dovetail joint (Trutnowy) b) lap joint (Trutnowy) c) dovetail joint (Klecie) d) lap joint (Klecie) e) mortise and tenon (Nowa Kościelnica) f) lap joint (Nowa Kościelnica)

Figure 7. The timber roof truss – current state: a) Trutnowy b) Klecie c) Miłocin d) Nowa Kościelnica

The dimensions of the roof truss components, the angle of inclination and the measure of used wood $\overline{V}$ of all investigated houses are collected in Table 2. The axial spacing of the rafters varies from 11.0 m to 12.3 m depending on the house. The measure of used wood $\overline{V}$ of the analysed houses ranges from 0.056 to 0.086 m^3/m^2, the average value $\overline{V}$ for all houses is 0.069 m^3/m^2. The angle of the rafters varies from 46° to 49°, which gives the average value for the five analysed objects of 47.2°, approximately 47°. The number of trusses is from 12 to 19, most often there are 17. In houses in Klecie and Trutnowy rafters with collars are connected with a dovetail notch, in the house in Nowa Kościelnica are connected with mortise and tenon. At the roof ridge (houses in Trutnowy, Klecie and Nowa Kościelnica), rafters are connected using lap joint.

The value of $\overline{V}$ can be compared with the study of Zybała (2019) on the roof structures of the 19th century portico houses from the Vistula Delta. These roofs are also of the collar beam type (with two collar beams), where the lower collar beam is supported by posts and purlins that strengthen the entire structure. The lower collar beam is covered with boards. This creates a wooden ceiling and increases the storage area of the attic. The greater number of structural elements present in the trusses (purlins and columns) increases the amount of wood used for the construction of the roof truss. The value of $\overline{V}$ is $0.075 m^3/m^2$.

Another difference between roof structures built in different centuries is how rafters are joined to the collar beam. In the oldest structures, they are connected with a dovetail notch. In the 19th-century rafter, the collar beam is connected with a simple lap joint.

The roof trusses of portico houses from the 17th-19th centuries also have common features. The angle of inclination of the rafters is almost the same. In the oldest buildings it is 47°, and 46° in the younger buildings from the 19th century. The connection of the rafters in the ridge are connected with a lap joint in all houses.

4. Global sensitivity analysis of roof construction in Klecie.

The roof of the portico house in Klecie is selected for the analysis due to the largest span of the truss, which is 12.30 m. It is assumed that one rafter differs from the other elements (Figure 8b), which may be the case in historic buildings. The right rafter has different material properties and geometry due to assumed moisture and decay. Uncertainties of properties of this one rafter are included in the analysis and their influence on the uncertainty of the mechanical response of the truss is investigated. Figure 8 shows the scheme of uncertainty propagation and sensitivity analysis, as described by

Sudret (2007). The probabilistic approach is used to investigate the influence of input uncertainties on the truss mechanical behaviour. The framework applied before to study traditional carpentry corner log joints by Kłosowski et al. (2018) is employed here. Firstly, FE models of the truss are built (Figure 8b). Uncertain inputs are identified and random input vectors are defined (Figure 8a). Next, uncertainties are propagated through the models (Figure 8c). Then, the influence of random variables on the output variance is assessed by the global sensitivity method (Figure 8d).

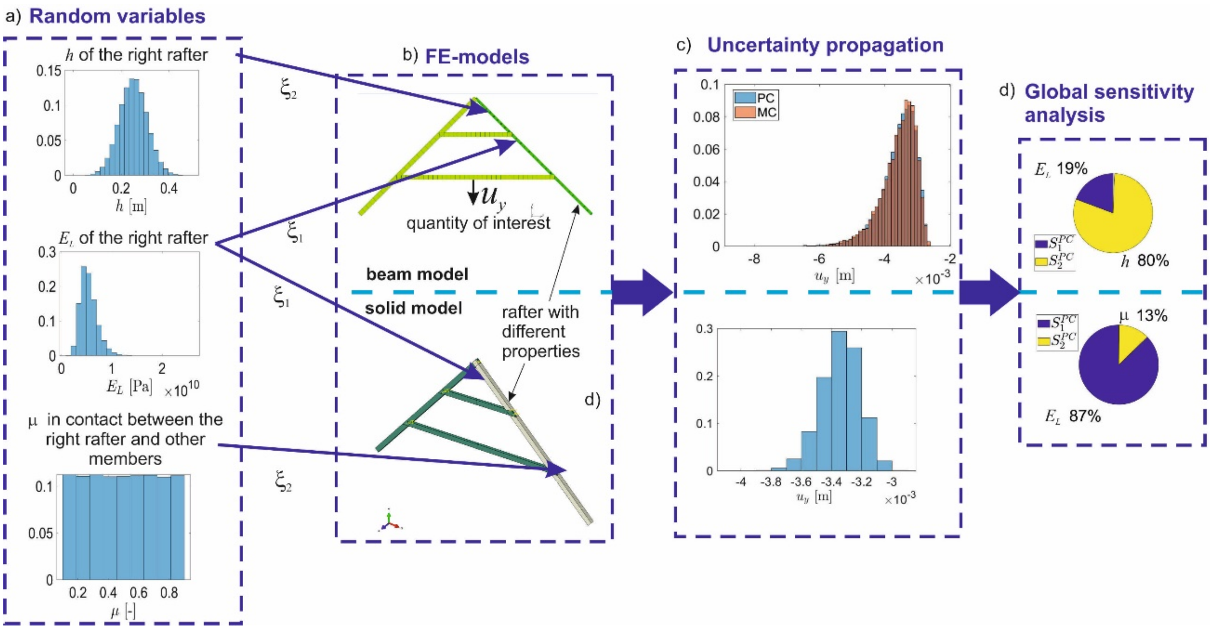

Figure 8. Scheme of uncertainty quantification and sensitivity analysis.

4.1 ***FE models and random variables***

Two numerical models, two-dimensional beam (Figure 9a) and three dimensional solid (Figure 9b), of the timber truss have been defined and analysed. Both models are compatible in terms of loading and material. The beam model is composed of 111 2-node finite elements with six degrees of freedom per node (Marc MSC Software). This element type includes transverse shear effects. The second, solid, FE model (Abaqus/Standard software) is discretised by 103668 stress/displacement 8-node linear hexahedral elements with three degrees of freedom in each node, reduced integration and hourglass control.

The finite element mesh was regular (Figure 9b) with an approximate element size of 2.5-3.0 cm. The model size has been reduced by modelling the bolts using kinematical coupling between the internal surfaces of the orifices in the roof truss joints and the reference points defined in the orifice centres (centres of bolts). The surface-to-surface contact discretisation was applied with the coefficient of friction between logs equal to 0.4 following Bedon, Rinaldin, and Fragiacomo (2015) except for μ friction coefficient between the right rafter of distinct properties and other timber members. Due to the wide range of reported values of the friction coefficient for wood-wood interaction (McKenzie and Karpovich 1968; Xu et al. 2014; Grossi et al. 2016), uniform distribution of μ is assumed in a wide range from 0.1 to 0.9.

The boundary conditions of the models mirrored the rafter supports on the building walls. Due to the way the rafter is connected to the tie-beam all translational degrees of freedom in each node of the support were fixed. In the beam model, the rotations were free in the support nodes (Milch et al. 2016). The roof truss was loaded with the weight of the roof covering based on (PN-EN 1990), the characteristic value was 164.62 N/m and snow load according to (PN-EN 1991-1-3) with the characteristic value of 130.56 N/m (Figure 9). The dead weight of all members was also included.

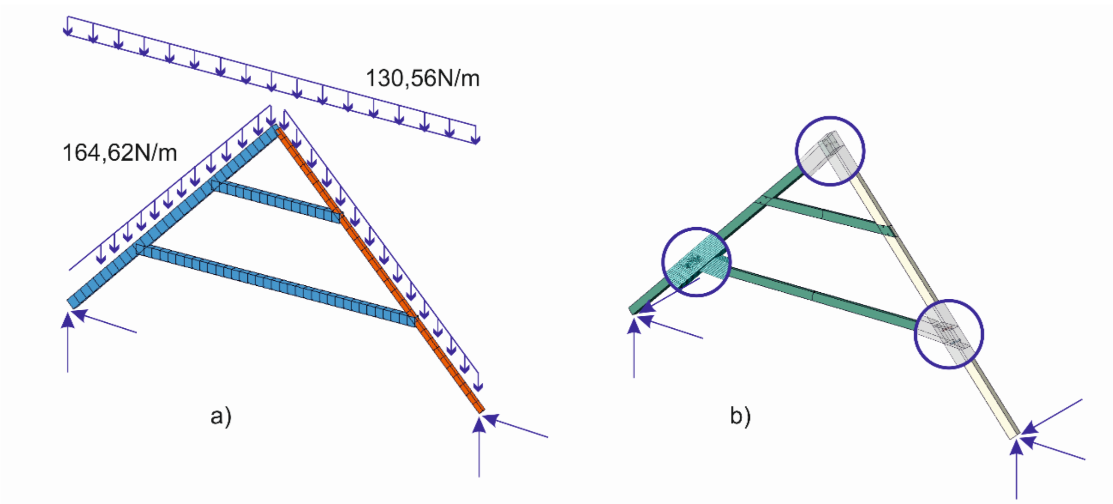

Figure 9. FE models of the roof truss: a) beam, b) solid; loading and boundary conditions

The cross sections of timber members are assumed according to the measurements results (rafters 20x25 cm, collar beams 14x24 cm). However, in the beam model the height h of the right rafter is assumed to be a normal random variable following the assumption of Brites, Neves, Machado, et al. (2013) on a cross-section distribution. The mean value is set to 25 cm, which is the value measured in the Klecie house. The coefficient of variation is assumed to be 23.1% based on the study of Lourenço et al. (2013) on the cross-section geometry of old timber structures. The value corresponding to the south rafter of the building of the eighteenth century is taken because this building is from the same century as Klecie house and also exhibits the highest variability. It is assumed that h is constant along the length of the rafter i.e. value of the random variable h is applied to the entire rafter. It should be noted, that normal distribution can lead to negative values of h which does not have physical sense and truncated normal distribution should be rather applied. Nevertheless, since in this case, the probability of negative h is very low and negative values were not obtained (Figure 8a), the classic normal distribution is assumed.

The truss material is Pinus sylvestris L., which is the most popular species of pine for timber structures in Poland, nowadays and in the past. It is assumed that the roof is made of old dry pine wood with exception of the right rafter which is made of old wet pine wood. As the wet wood becomes weaker it can also represent degraded material. The properties of wood change with the direction of fibres, so the orthotropic elastic material model is assumed here. Its parameters are set up following Lubowiecka et al. (2019). The E_L is a longitudinal modulus of elasticity (along the direction of the fibres) of dry wood equals to 11.95 GPa, which is value based on the experimental identification of nineteenth century wood. Following the work by Kłosowski et al. (2018) the moduli of the radial –

R and tangential – T directions are assumed to be related to E_L according to the formulae E_T / E_L = 0.068, E_R / E_L = 0.102, G_{RT} / E_L = 0.005, G_{TL} / E_L = 0.046, G_{LR} / E_L = 0.049, where G is a shear modulus. The appropriate Poisson ratios are determined as ν_{RT} = 0.469, ν_{TL} = 0.024, ν_{LR} = 0.316 according to Green et al. (1999). E_L of right rafter is assumed to be random variable. The wood exhibits high natural variability of properties (e.g. Machado et al. 2019) and what is more properties depend on the moisture and decay (Sousa et al. 2014). Following recommendations of JCSS (2006) the lognormal distribution is assumed LN (22.37, 0.301) with parameters adjusted in the MATLAB distribution fitter toolbox to the experimental data on wet nineteenth-century wood (Lubowiecka et al. 2019). It is assumed that other moduli vary together with E_L so the aforementioned ratios are constant.

To sum up, the advantages of two modelling strategies are taken and two models are used to propagate uncertainties of different sources. Both models have two random variables due to the uncertainties. In the beam model first random variable is E_L, and the second is h. In the solid model the first random variable is also E_L, but the second one is μ (Figure 8a). It is easy to vary cross-sectional parameters in case of the beam model, whereas it would be more challenging to do in case of solid model. On the other hand, the solid model enables to reflect more accurately the behavior of timber joints including contact, which was on contrary not accounted in the beam model. The choice of random variables is related to practical issues in modelling of timber trusses. Precise values of E_L and μ are hardly known due to high natural variability of wood and due to challenges in their accurate non-destructive identification. Cross-sectional dimensions can be measured accurately, but the process is time consuming, so in practice not always undertaken, especially in preliminary phase.

The output on which the analysis is focused (quantity of interest) is a displacement u_y (displacement along the gravity direction) of the node on the collar beam (Figure 8b), where the displacement for the mean parameters is the highest. The reason is that the serviceability limit states is more often cause to investigate timber structures than ultimate limit states (Morales-Conde and Machado 2017).

4.2 ***Global sensitivity analysis with Polynomial Chaos expansion framework***

Uncertainty quantification (UQ) in the case of using commercial FE software can be performed by non-intrusive methods. These methods do not require FE code modification and are based on a number of deterministic simulations. Therefore such methods can be easily applied even to non-linear models with contact. Monte Carlo (MC) is a widely used non-intrusive method, but it requires a very high number of simulations to be performed to propagate uncertainties. The number of simulations is getting even higher when also Sobol' indices as a global sensitivity measure (Sobol′ 2001) are to be computed. Polynomial Chaos (PC) in non-intrusive variant (Sudret 2008) is a method of constructing meta-model and has become recently widely used alternative to crude MC reducing the computational cost of uncertainty quantification and global sensitivity analysis. The following description of the methods is partially based on (Fajraoui et al. 2017).

The output (quantity of interest) Y of model f can be approximated by a meta-model f_{PC} with the use of truncated expansion as follows:

$$Y \approx f_{PC}(\boldsymbol{\xi}) = \sum_{\boldsymbol{\alpha} \in A} a_{\boldsymbol{\alpha}} \boldsymbol{\Psi}_{\boldsymbol{\alpha}}(\boldsymbol{\xi}), \tag{2}$$

where $\boldsymbol{\xi} = [\xi_1, \xi_2, \ldots, \xi_M]^{\mathrm{T}}$ is the M-dimensional input vector of reduced independent random variables. Normal and lognormal variables are firstly needed to be transformed into standard normal variables and uniform one to a uniform variable with support $[-1, 1]$

. $a_{\boldsymbol{\alpha}}$ are PC coefficients, A is a truncation set, $\boldsymbol{\Psi}_{\boldsymbol{\alpha}}(\boldsymbol{\xi})$ is a multivariate polynomial basis constructed from multiplying univariate polynomials ψ_{α_i} of degree α_i:

$$\Psi_{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \prod_{i=1}^{M} \psi_{\alpha_i}^{(i)}(\xi_i), \tag{3}$$

where $\boldsymbol{\alpha}$ is a multi-index $\boldsymbol{\alpha} = [\alpha_1, \ldots, \alpha_M]$. The used polynomials are orthonormal. Therefore, Hermite polynomial is employed in case of normal variables, and Legendre polynomials in case of uniform distribution. The classic truncation method is used. Multivariate polynomials of degree less or equal to established order p are taken, so the truncation set A is:

$$A = \{\boldsymbol{\alpha} \in \mathbb{N}^M : \sum_{i=1}^{M} \alpha_i \leq p\} \tag{4}$$

Then the cardinality P of the set A is:

$$P = \left|A\right| = \binom{M+p}{p} = \frac{(M+p)!}{M!\,p!} \tag{5}$$

The coefficients $a_{\boldsymbol{\alpha}}$ can be found non-intrusively by least square regression. N regression points have to be chosen $[\boldsymbol{\xi}^{(1)}, \ldots, \boldsymbol{\xi}^{(N)}]$. The accuracy of the non-intrusive method depends on the number and choice of sampling points. Here, following our previous experience with problems with a low number of random variables (Szepietowska et al. 2018), a D-optimal solution from a randomly chosen candidate set is chosen . The vector of exact solutions is created by evaluating model f on the chosen points $Y_{ex} = [f(\boldsymbol{\xi}^{(1)}), \ldots, f(\boldsymbol{\xi}^{(N)})]^{\mathrm{T}}$. Then the coefficients $\mathbf{a} = [a_{\boldsymbol{\alpha}0}, \ldots, a_{\boldsymbol{\alpha}P-1}]^{\mathrm{T}}$ can be calculated by solving:

$$\mathbf{a} = (\mathbf{\Psi}^{\mathrm{T}}\mathbf{\Psi})^{-1}\mathbf{\Psi}^{\mathrm{T}}Y_{ex}, \tag{6}$$

where $\Psi_{ij} = \Psi_{\boldsymbol{\alpha}_j}(\boldsymbol{\xi}^{(i)})$, $i = 1,\ldots,N$, $j = 1,\ldots,P$.

Meta-model f_{PC} may be used to perform many simulations with negligible computations cost. What is more, some values may be estimated directly from coefficients, e.g. the mean value equals $a_{\mathbf{0}}$ and variance is:

$$D \approx D_{PC} = \sum_{\boldsymbol{\alpha}\in A\setminus\{\mathbf{0}\}} a_{\boldsymbol{\alpha}}^2. \tag{7}$$

Sudret (2008) shown that also Sobol' indices may be computed using PC coefficients. Sobol' indices are global sensitivity measures based on ANalysis Of VAriance (ANOVA) decomposition. Sobol' index (Sobol′ 2001) $S_{i_1,\ldots,i_s}$ expresses how much of the output variance is due to the given input variables $i_1,\ldots, i_s$. $S_{i_1,\ldots,i_s}$ can be estimated using coefficient corresponding to polynomials depending only on all input variables $i_1,\ldots, i_s$ as:

$$S_{i_1,\ldots,i_s} \approx S_{i_1,\ldots,i_s}^{PC} = \frac{1}{D_{PC}} \sum_{\boldsymbol{\alpha}\in A_{i_1,\ldots,i_s}} a_{\boldsymbol{\alpha}}^2, \tag{8}$$

where:

$$A_{i_1,\ldots,i_s} = \{\boldsymbol{\alpha} \in A : \alpha_k \neq 0 \Leftrightarrow k \in \{i_1,\ldots,i_s\}\}. \tag{9}$$

and total Sobol' index S_i^{Tot} is the sum of all indices corresponding to the i-th variable:

$$S_i^{Tot} \approx S_i^{Tot,PC} = \frac{1}{D_{PC}} \sum_{\boldsymbol{\alpha}\in A_i^{Tot}} a_{\boldsymbol{\alpha}}^2, \tag{10}$$

where,

$$A_i^{Tot} = \{\boldsymbol{\alpha} \in A : \alpha_i \neq 0\}. \quad (11)$$

Relative Leave-one-out error estimate may be used to control accuracy of PC meta-model (Fajraoui et al. 2017):

$$E_{LOO} = \sum_{i=1}^{N} (\frac{f(\boldsymbol{\xi}^{(i)}) - f_{PC}(\boldsymbol{\xi}^{(i)})}{1 - h_i})^2 \;/\; \sum_{i=1}^{N} (f(\boldsymbol{\xi}^{(i)}) - \hat{\mu}_Y)^2, \quad (12)$$

where h_i is the i-th diagonal term of matrix $\boldsymbol{\Psi}(\boldsymbol{\Psi}^{\mathrm{T}}\boldsymbol{\Psi})^{-1}\boldsymbol{\Psi}^{\mathrm{T}}$ and $\hat{\mu}_Y = \frac{1}{N}\sum_{i=1}^{N} f(\boldsymbol{\xi}^{(i)})$

Additionally, in both models: the PC is calculated for a couple of orders p. What is more, crude MC simulations were performed additionally for a less expensive computationally beam model as a reference solution.

4.3 ***Uncertainty quantification and global sensitivity analysis results***

The uncertainty quantification and sensitivity analysis results are presented in Table 3 and Figures 8c-d, 9, 10. In the case of the beam model, the relative differences between PC results and reference MC solutions are small and do not exceed 5% even for the lowest considered PC order 2. Accuracy of the PC can also be observed in Figure 8c (top part) showing overlapping histograms of quantity of interest obtained by PC order 3 and MC method. However, often, as in the case of the solid model, the cost of the MC solution is not tractable. The relative differences of S_1^{Tot} between PC of order 2 and 3 is around 6% in case of the beam model. In other cases, the relative differences are smaller. In all cases E_{L00} error is also relatively small (in the range of 0.013-7.05E-04 in case of the beam model and 0.0059-1.87E-4 in case of the solid model). Therefore, one may conclude that the accuracy of PC approximation in those cases is satisfactory. In the following description, numerical results are given for the solution obtained by PC of order 3.

In case of the beam model, a high value of $S_2^{Tot} = 0.81$ indicates that uncertainty of *h* has high influence on the variance of the output quantity of interest when compared to the uncertainty of E_L($S_1^{Tot} = 0.2$). From the point of view of conservation practice, this conclusion may be seen as favourable, because it is easier to measure accurately cross-sections of the timber members than to non-invasively identify Young modulus. It should be noted, that a higher influence of *h* is obtained despite lower input variation of *h*.

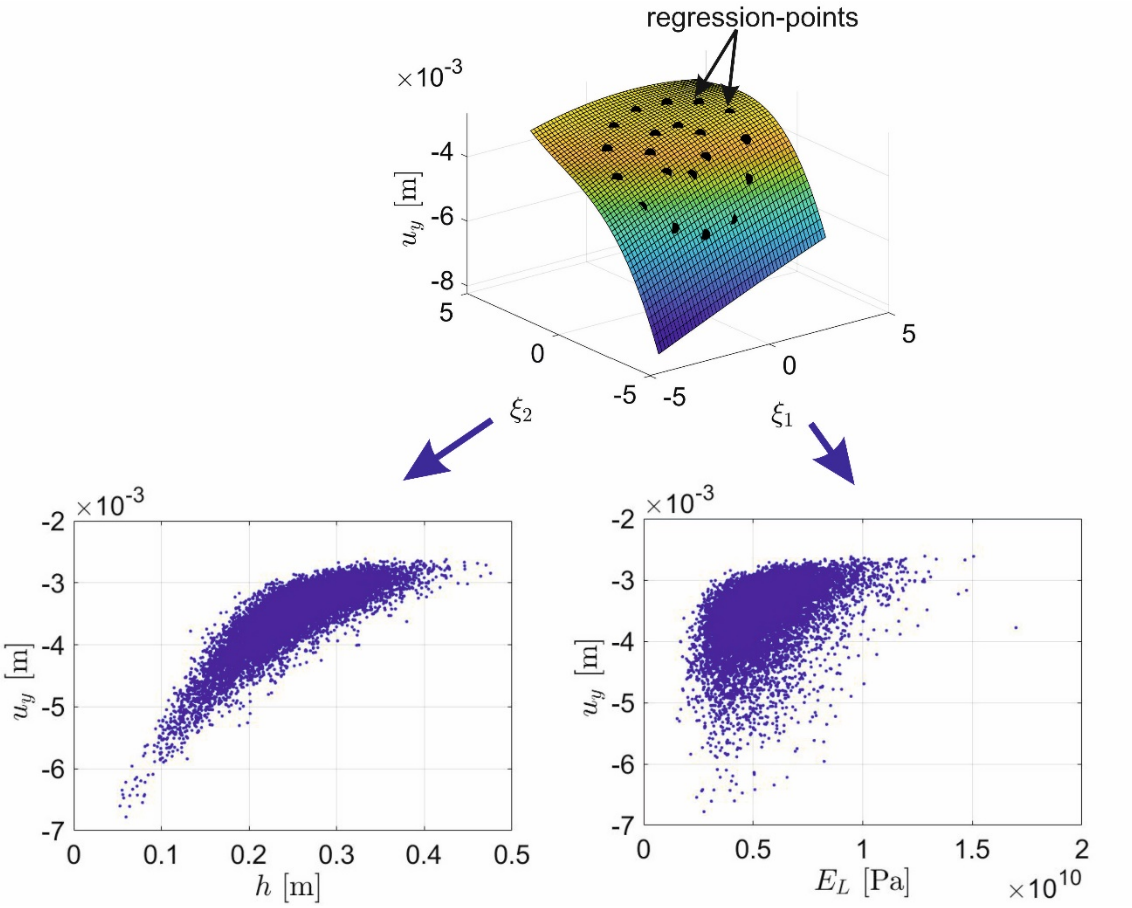

Figure 10. PC meta-model of quantity of interest obtained by the beam model with regression points marked (top) and scatter plots of MC sampling points (bottom)

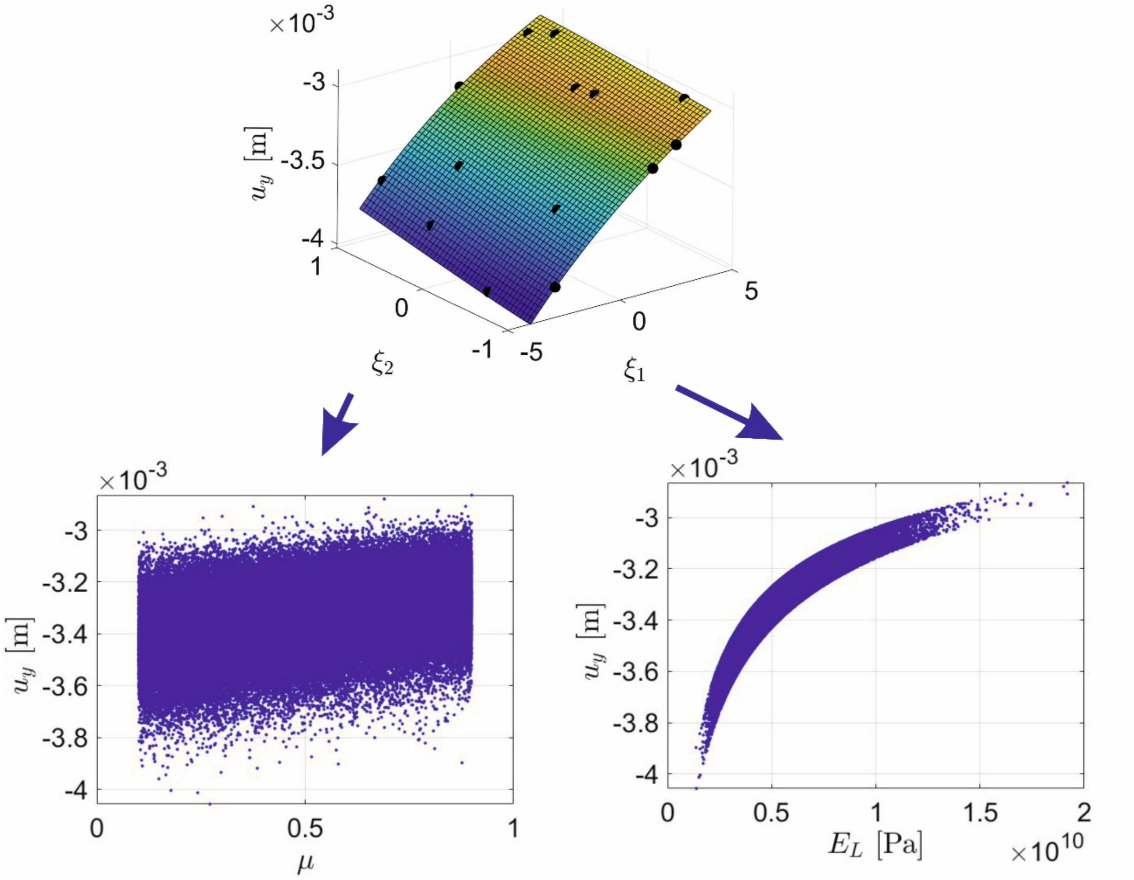

Figure 11. PC meta-model of quantity of interest in case of solid model with regression points (top) marked and scatter plots of 105 sampling points and the quantity of interest computed with use of PC meta-model (bottom)

In case of the solid model, E_L has, however, a dominating influence on the uncertainty of u_y when compared to μ, which is indicated by a very high value of $S_1^{Tot} = 0.874$ and low of $S_2^{Tot} = 0.127$. Again these conclusions may be seen as a positive from a practice point of view, since accurate identification of friction coefficient in a non-invasive way would be challenging.

Sensitivity of the outcome to the considered uncertainties can also be visualised with the use of scatter plots (Figures 10-11, bottom part), which show the relation between the model output and each random variable.

Table 3. Results of uncertainty quantification and global sensitivity analysis

Model	Beam model				Solid model	
Method	MC	PC order 2	PC order 3	PC order 4	PC order 2	PC order 3
Mean [mm]	-3.6	-3.6	-3.6	-3.6	-3.3	-3.3
Standard deviation [mm]	0.554	0.560	0.560	0.552	0.131	0.130
S_1^{Tot}	0.2017	0.2106	0.1988	0.2006	0.879	0.874
S_2^{Tot}	0.7941	0.8004	0.8069	0.8056	0.1225	0.1273
E_{Loo}	-	0.0013	0.0012	7.05E-04	0.0059	1.87E-04

Figures 10 and 11 show meta-model surfaces obtained for PC order 3. The non-linear character may be noticed. Local sensitivity indices studying the influence of small variations around a single point are hence different for the different initial points. For example, in the case of the solid model, the relative coefficient of local sensitivity of u_y on the variation of μ around value 0.4 (ξ_2 = -0.25) is equal to 2.4E-2 when E_L equals 2.106 GPa (ξ_1= -3) and 1.6E-2 when E_L is equal 12.817 GPa (ξ_1= 3). The fact that the higher E_L, the lower influence of μ, can be noticed also by the shape of the surface response (Figure 11). Relative coefficients of local sensitivity are calculated by numerical central differencing like by Lubowiecka et al. (2019), where the influence of Young Modulus on the behaviour of carpentry corner joints was investigated.

The histograms of the quantity of interest are shown in Figure 8c. The coefficient of variation of quantity of interest (u_y) is equal to 16% in the case of the beam model and 4% in case of the solid model. The much lower value in the latter case can be explained by the fact that less important input variables are taken into account in the solid model. The h which is responsible for the majority of the variance in the beam model is not treated as a random variable in the case of the solid model. The mean of u_y obtained by beam and solid model having a different set of random variables are relatively similar, -3.6 mm in the first case, and -3.3 mm in the latter one.

5. Conclusions

The oldest portico houses of the Vistula Delta dating to 17th and 18th centuries have been presented in this paper. The analysis of these historic buildings in comparison to newer houses from the 19th century shows the alterations that have occurred in their roof structures over the centuries. The changes in the volume of timber used for the construction of the roof truss, as well as the differences in their structure may be helpful in determining the age of given houses. The technology used for construction and carpenters' marks visible on the joints confirm the age and authenticity of the roof structures.

It is worth noting the good technical condition of the roof structures in the houses analysed from the 17th and 18th centuries. This is caused by several factors. Homeowners make repairs systematically. In all buildings, the roof coverings are raintight, the attics have gravity ventilation (constant air circulation maintains the correct moisture of the wood), and there are no additional loads. This situation augurs well for the proper preservation of the historical structures in centuries to come. Such a way of maintenance is consistent with the principles of monument conservation and may be used in all wooden roof structures.

Nevertheless, to effectively plan for the future conservation of these ageing monuments, knowledge is needed of the sensitivity of the mechanical response of trusses to uncertainties caused by the limitations of the relatively crude preliminary measurements and structural analysis.

The polynomial chaos method enables the construction of sufficiently accurate meta-models to study with low computational cost the influence of uncertainties of properties of one rafter, i.e. Young modulus, cross-section height and friction coefficient, on the deflection of the roof truss. These uncertainties reflect natural variability and the lack of sufficient data at the stage when structural analysis outcomes are already needed to assess a historic structure. The proposed approach can be applied to historic timber roofs of similar complexity.

The information provided about global sensitivity can be used to formulate recommendations for further studies: both numerical and experimental. The results show the importance of uncertainty of cross-sectional height in the modelling of timber trusses. Uncertainty of this geometric parameter has a greater influence on the quantity of interest than the uncertainty of the longitudinal modulus of elasticity, what is shown in the case of the beam model. The uncertainty of longitudinal modulus of elasticity has a higher contribution to the variance of the output of the solid model than the uncertainty of friction coefficient. Therefore, it can be concluded that including uncertainty of the coefficient of friction in the modelling is of lowest importance, whereas cross-sectional uncertainty is of highest importance. The same ranking can be established to set priorities in experimental works. It should be noted that, uncertainty of the geometric parameter was included only in the beam model and consequently the output variance obtained in this model was higher than in case of the solid model. Taking all of the above into consideration, a numerical analysis of similar complexity could be performed using only a beam model in the future. This will be easier in definition and faster in calculation what is especially favourable in case of uncertainty propagation when a set of simulations is needed. However, if more complex analysis requiring detailed description of the joint is to be performed on a solid model, the uncertainty of the cross-sectional dimension should also be taken into account in such a model.

The results help to prioritize studies of historic trusses of portico houses. The uncertainty of cross-sectional height has the greatest influence on the variance of the deflection. Therefore, the future field survey should be concentrated on the measurements of cross-section dimension. Accurate identification of timber member cross-sections, for instance using laser scanning, would decrease the uncertainty of the predicted deflection in the most effective manner. The influence of the uncertainty of the cross-section may be even more important since it also affects assessment of the modulus of the elasticity by non-destructive testing (Morales-Conde and Machado 2017, Osuna-Sequera et al. 2020). What is more, the attention should be paid to the dimensions of the new elements replacing the damaged timber members.

It should be noted, that all random variables are independent and spatial variability is not included, which is a limitation of the study. To capture imperfections or geometrical irregularities of the surfaces usually observed in old constructions, random fields should be employed. Nevertheless, the results obtained indicate that it is worth studying in more detail the uncertainties of geometry in the type of structure analysed. In the future studies, distribution of cross-sectional parameters should be more accurately identified.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

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