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Abstract

The wooden log house serves as a prevalent architectural archetype in rural regions of several Nordic and Baltic countries. To ensure the long-lasting nature of these buildings, proper maintenance is imperative. However, in order to meet the evolving expectations of residents and minimize the environmental impact, a deep renovation is currently required. To successfully achieve the goals of this renovation wave and effectively address the personal needs of the homeowners, it is crucial to develop systemic renovation solutions that can be offered through a digital renovation passport. Consequently, the purpose of this study is to identify common damages, renovation requirements, and evaluate current renovation practices. The findings will serve as a crucial resource for the development of a digital renovation passport. In our study, we utilize rural wooden log houses (comprising 208 houses, 4 years of data) as our research subject. The building elements that are most in need of renovation are the external walls, roofs, and foundations, which require renovation in 77%, 63%, and 63% of the buildings, respectively. The primary cause of damage to the vulnerable structures is excessive moisture. Additionally, decay in the foundation can be attributed to factors such as erosion of mortar, frost, insufficient plinth height, inadequate foundation depth, and inadequate moisture protection. Recommendations provided by consultants primarily focus on restoring and preserving the dwellings' original architectural appearance. As a result, they are deemed insufficient in terms of improving energy performance and indoor climate. This lack of comprehensive consultation is concerning as it fails to consider the potential for cost efficiency, minimizing disruption to occupants, and achieving a comprehensive end result. The absence of recommendations for enhancing indoor climate, energy efficiency, general living quality, and reducing the building's carbon footprint performance highlight the necessity for such renovation

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solutions and the importance of educating professionals and homeowners. The study's novelty lies in the establishment of statistical probabilities for damages and their causes, as well as the assessment of renovation and maintenance needs and the quality of existing recommendations. Results are scaled to the Estonian building stock, showing the renovation need on national scale. The findings can be incorporated into the digital renovation passport, along with specific renovation goals related to a given house.

Keywords: renovation strategy; building vulnerability; durability; service life; renovation passport; wooden log house.

Introduction

In Baltic states the share of population that reported their health status as fair, bad or very bad was about 50 % - highest in Europe. Just over one third (35 %) of the population live in detached houses in EU (Eurostat, 2018). Le et al. (2011) studied vernacular drystone retaining walls and showed that they can be subject to slow deterioration due to the weathering of the materials, application of loads for which they were not designed, impact, or inappropriate repair methods.

Many rural buildings may be used temporarily during summer, when heating energy use is low. In this case energy renovation could be not needed and may be even more less cost optimal (Alev et al., 2015). Nevertheless, the COVID-19 pandemic changed the use of historic rural buildings – many houses that were used only temporary during summer were used as normal houses also during winter heating period. For example, residential energy use in the United States increased by 6–8 % in 2020 compared to 2019 (IEA, 2020).

Deep energy renovation may result in relatively large investments that may not be cost optimal. Nevertheless, minimizing energy may not be the only reason for building renovation. Tommerup et al. (2010) showed that by linking the extensive energy savings to the normal renovation measures, such as eliminating physical degradation, bad thermal indoor comfort, health problems or improving overall architecture and use of the house, is a way to reduce the price of implementing the savings.

Buildings and its components are designed to have long service life, traditionally 50 years. In practice we can see considerably shorter (Kalamees, 2002) or longer (Kayo & Tonosaki, 2022). Changes in climate in the Baltic region has potentially increased the rate of decay for wood material, as rising average temperatures and annual precipitations potentially create more advantageous conditions for biological growth and decreased periods for drying (Lisø et al., 2006). This increases the need for maintenance and identifying signs or potential for damages before a notable decline in condition can occur. The longer a building lasts, the lower its annual average life cycle embodied energy demand (Rauf & Crawford, 2015).

In Estonia, the most notable increase in renovation activity is required among detached houses in order to achieve a decarbonized building stock. Approximately 30 % of the detached housing stock in Estonia has been built before World War II (LTRS, 2020). The dominant building archetype of detached houses during this period in Estonia was the wooden log house, which constituted the majority of structures in rural areas (Statistics Estonia, 2021). These buildings represent an important part of Estonian architectural heritage. Since the houses were built by the residents themselves or by local masters, the structures used can be very different with variable quality. For the renovation strategy action plan at the national level, it is imperative to have insight into likely volumes of renovation works and construction materials.

In order to assist and guide home-owners through the renovation process, existing Energy Performance Certificate (EPC) concept in the EU is recommended to be developed into Building Renovation Passport (BRP), which would provide a tailored long-term renovation and maintenance roadmap for each building (Sesana & Salvalai, 2018). The viability of a digital-twin based renovation strategy tool for producing and communicating typology-based renovation solutions is currently under evaluation in Estonia (Iliste et al., 2023). In order to get a sufficient overview of the buildings' pre-renovation technical situation and the need for renovation, a comprehensive overview is needed. Fig. 1 shows, where survey and audit of pre-renovation technical state positions in renovation passport concept. Current study uses Estonian wooden log houses from WWII period as an example building archetype.

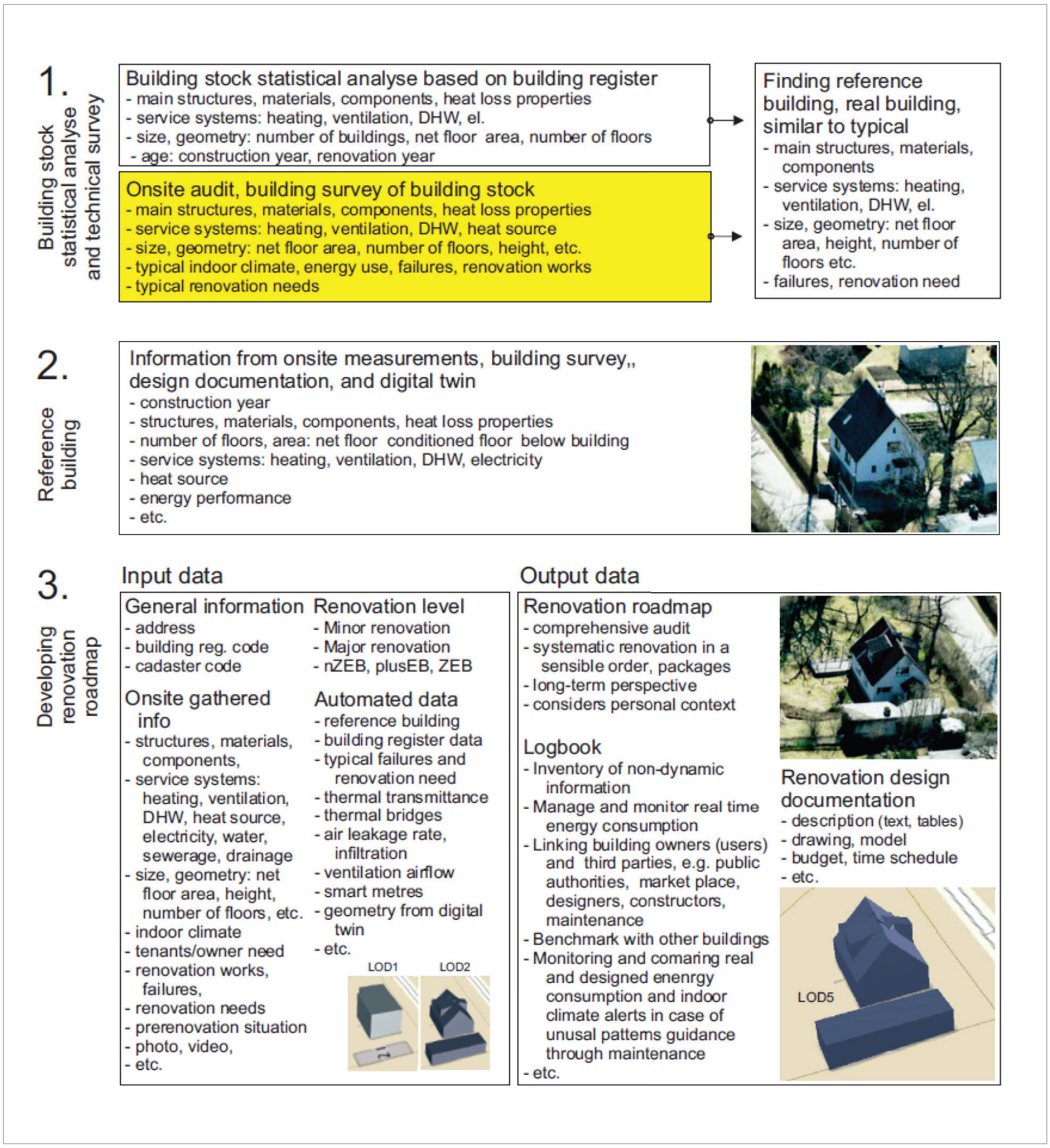


Fig. 1

Renovation strategy / renovation passport concept (based on authors idea and (Fabbri et al., 2016)). Yellow area shows the position of the current work into renovation passport

Methods

Database and it's analysis

We analysed the database of building survey and consultation reports collected between 2019 and 2023 by a national network of consultants (35 active consultants from different backgrounds), initiated by the Estonian Open Air Museum's Centre of Rural Architecture. The database of reports included more than 300 buildings, summed up to more than 1000 investigated structures and building components. The purpose of building survey and consultation was to determine renovation need of houses and to give recommendations to homeowners for further repair and renovation of the house. All building surveys were based on the same questionnaire. Depending on the need and condition of the house, the expert used a visual and structural inspection. During the inspection of the condition of the house, recommendations were also given on which materials to use and where to start the work. Finally, the homeowner received a description of the current situation and a brief summary of renovation recommendations.

All consultation reports were submitted into an online form, which is then collected into a database. Every consultation report is partitioned between surveyed structures, such as the foundation, walls, floors, windows, etc. Each building structure may then be described in a free text field, highlighting the material, condition, damages, specific details or any other information deemed relevant by the consultant. For this reason, the findings of the study will represent only consulted structures and buildings, and details or structures not present within the reports may have other types of damages not highlighted with this study. For example, building service systems such as ventilation or sewerage, were generally not included within the consultation reports. In some cases, a described detail may not even be damaged, but instead highlighted to be in good condition. The consultant is also asked to include photographic material whenever relevant and describe a repair or renovation solution.

The data within the database of building survey and consultation reports was exported into a single MS Excel table in order to improve the potential for data analysis. This data was then structured and analysed based on keywords concerning building type, building structure, construction material, construction elements, damages, recommendations, etc. The variety and statistical frequency of mentioned building structures, damages and recommended renovation solutions is then highlighted. Consultation reports were structured into building components, such as foundations, walls, floors, ceilings, windows, doors, roofs, heating systems or other miscellaneous aspects. Each sub-report concerning a building part then describes the material, condition, damages, specific details or any other information deemed relevant by the consultant. This analysis will then provide statistical overview of pre-renovation technical condition and renovation need among the studied buildings, as well as evaluation of renovation recommendations communicated by consultants to home-owners. This data can then be used to highlight the most vulnerable structures and nature of likely damages, as well as causes, for developing typology-based renovation strategies and solutions.

Studied houses

All studied buildings generally date from a time period between 1851 and 1950, with few exceptions of earlier or later periods. The most common building types within the consultation report database of 308 buildings were found to be the detached house (41 %; 127 buildings) and the barn-dwelling (an archaic type of house with kiln room for drying grain, threshing floor, and chambers where people worked and slept) (31 %; 94 buildings). All other building types were either not residential in function or were negligible in terms of sample size (<7 %) and were therefore excluded from the analysis.

The most common external wall within the narrower sample of houses was horizontal log (94 %; 208 buildings). All other construction types had a negligible sample size and were excluded from both the study and article. Therefore, the total number of buildings included in the study was 208, consisting of 115 detached houses and 93 barn-dwelling (houses were analysed together when archetype did not account for large difference regarding technical state before renovation and the renovation need). The relatively high number of barn-dwellings within the study (45%) needs to be highlighted when considering possible generalisations of the results, as the maximum number of surviving barn-dwellings in Estonia can form no more than 12% of the detached housing stock built before World-War II (Lõuk, 2013; LTRS, 2020). For this reason, damages more characteristic to barn-dwellings can be somewhat overly represented among the proportions of renovation need.

To scale renovation need and volume for the whole wooden houses stock we used the dimensions and properties of two typical houses (a barn-dwelling and a detached house) built before World-War II in Estonia (Alev et al., 2015) and building register data (http://ehr.ee/, 2023).

Results and discussion

Studied houses and the main vulnerable structures

By size, based on Estonian National Register of Buildings (http://ehr.ee/, 2023) data, the average living area of barn-dwellings was 197 m^2 (range between 100 m^2 and 350 m^2) and of detached houses was 124 m^2 (range between 50 m^2 and 250 m^2).

Wall, roof, and foundation were structures most frequently mentioned in survey as needed to be renovated (Fig. 2). A number of structures within the database described a good condition or did not provide details concerning renovation need. Structures concerning heating were highlighted as well, yet due to low level of detailed data, these were excluded from further analysis in the current study. Barn-dwellings were mentioned more in all structure categories, which indicates more vulnerable structures and a greater need for renovation comparing to common detached houses. Another explanation for this is the older age of the barn-dwellings. Our findings are supported by Dutu et al. (2023), who showed that the most of the damage and degradations that occur in almost all traditional timber houses are related to water infiltrations and humidity – the wall, roof and foundation are in contact with the highest moisture loads. Although houses with a different basic typology, these structures have been determined also by other studies to be the most vulnerable. Nowogońska & Mielczarek (2021) studied abandonment of renovations and found that the most urgent renovation works are the renovation of the foundations and walls. Lourenço et al. (2006) presented the need to renovate the roof or facade due to water seepage and condensation in buildings from historical city centres in Portugal. In Norway (Risholt et al., 2013), the foundation was also one of the most defective building elements, but wet rooms and windows replaced the roof and exterior wall in acute need for renovation. In Finland serious damage from moisture has been found in 82 % of detached houses (mainly wooden) built since the 1950s, concentrated to wet areas, base floor structures and the joints between the base floor and wall structures (Heikkilä, 2005). Therefore, building surveying and renovation measures should always be carried out to structures that can be in contact with excess humidity. The current study, however, does not include detailed information concerning wet rooms due to low occurrence among the studied buildings or lack of focus among consultants on such structures. The walls, roof and foundation, are also structures that should be renovated to minimize heat loss (Alev et al., 2014). Thus, by combining the two goals in renovation of buildings, it is possible to get a double benefit. Fig. 3 and Fig. 4 presents the locations and reasons for damages and renovation need, described in detail in following chapters.

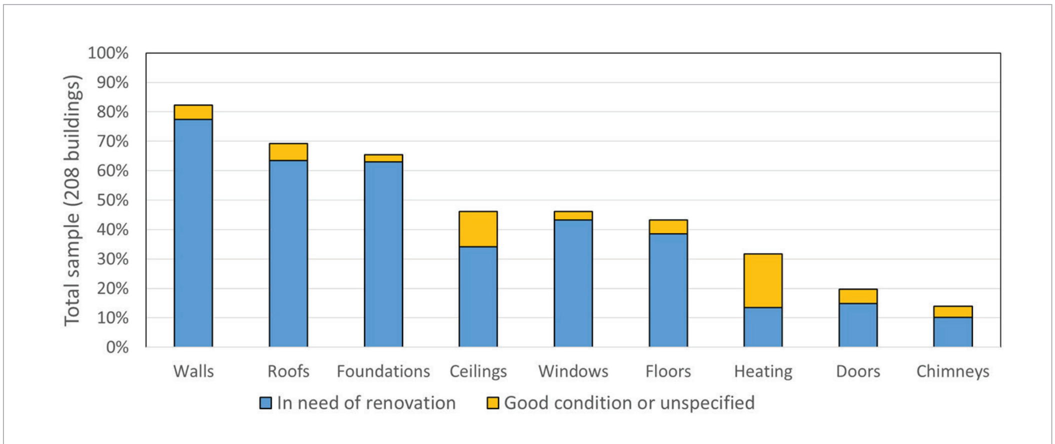


Fig. 2

Frequency of consulted structures and corresponding renovation need included in consultation reports of 208 examined houses

Fig. 3

Typical connection detail of external wall, foundation, and floor with typical damages and renovation needs

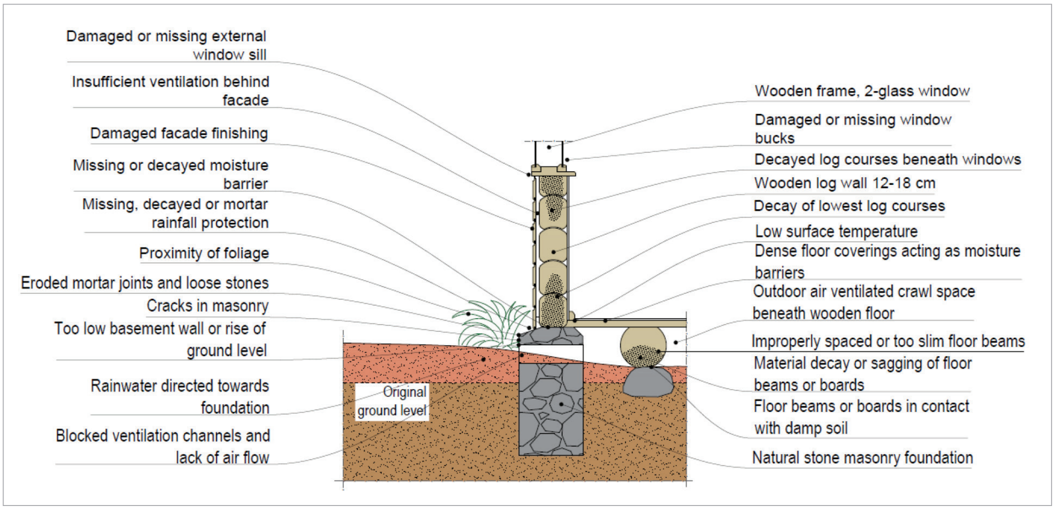
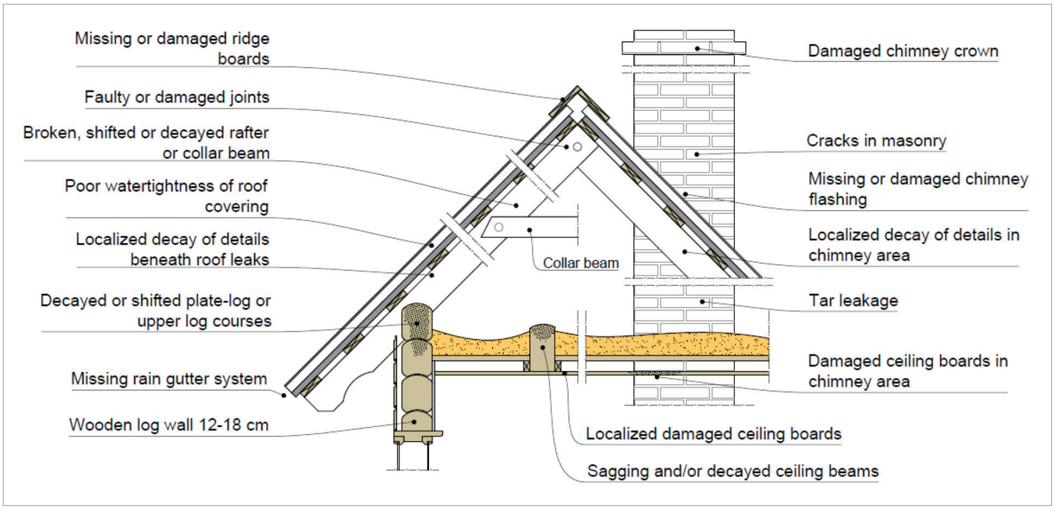


Fig. 4

Typical connection detail of external wall, roof, attic floor and with typical damages and renovation needs



Foundation

Renovation need of foundations was highlighted for 96 % of foundation reports, constituting 63 % of all sample houses. From these foundation reports, 91 % were constructed from a natural stone material (limestone or granite) and 9 % from concrete, indicating a greater need for renovation of natural stone foundations. Foundations generally have rainfall protectors, usually slanted horizontal wood boards or flashing covering the external upper edge of the foundation, are in constant contact with moisture during precipitation. In total, nearly all (excluding 5 reports) foundation's reports highlighted damages or details needing attention.

The main damages of foundations and their causes

The three most common types of damages among natural stone foundations, present in 71 % of foundation reports, were: crumbled mortar joints (51 %), cracks in the masonry (25 %), and loose stones (13 %) (Fig. 3, Fig. 5 above). Causes for these damages were related to rainwater degradation (which will increase in future during winter (Bonazza et al., 2009)), insects (for example, ants) and natural weathering from passage of time. Wet masonry is also in risk of eroding due to freeze-thaw cycles in cold climates (Grossi et al., 2007). The introduction of moisture can be due to precipitations, where the lack of a functioning rainfall protector (highlighted in 37 % of foundation reports), insufficient foundation wall height (38 %) and ground slopes directing rainwater towards the foundation (31 %) will allow water to infiltrate the structure. Examples of poorly designed or installed rainfall protectors were found among 14 % of foundation reports, generally highlighting mortar-based rainfall protectors (which trap moisture between the foundation and lowest course of logs), or wood elements either too slim or without a slant to properly direct the rainwater away from the foundation. The precise height of a too low foundation wall was generally not specified in consultation reports, but anything less than 300 mm would be non-optimal, as a low ground floor can lead to moisture damages in wood structures in contact with the stone foundation wall (Taylor et al., 2023). Other means for contact with moisture can be foliage too close to the building (8 %), where flowerbeds or bushes in proximity to the foundation wall will create a moist environment, or from capillary rise from the ground (Asphaug et al., 2020). For this reason, problems with moisture barriers between the stone foundation and log wall were highlighted in 21 % of foundation reports.

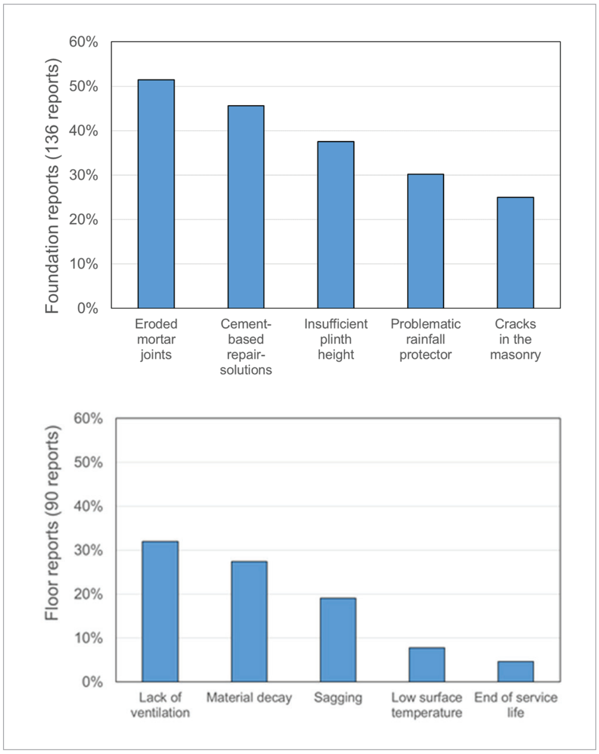


Fig. 5

The main damages present in consultation reports concerning foundations (above) and floors (below)

Foundation renovation recommendations by consultants

In order to eliminate foundations damages, the consultants have recommended removing loose mortar joints and foundation stones before repairing or reconstructing the structure with appropriate lime-based materials. Repairing the rainfall protector generally concerned either installation, repair or replacement with a new wooden board with proper width and slope. This solution is not guaranteed to have an optimal service-life, however, as without additional flashing or other covering, the wood element will begin to decay yet again. Mortar-based rainfall protectors were all recommended to be removed, as contact between mortar and wood elements ought to be avoided in foundations (Alev & Kalamees, 2016).

Most foundations were deemed salvageable, with 40 % of foundation reports highlighting only light repair works, such as applying fresh mortar to noticeably decayed mortar joints (22 %). Another 40 % of foundation reports recommended more extensive repair works, such as re-applying or replacing stones in addition to lighter repairs. The final 20 % of foundation reports recommended replacing either the entire or part of the foundation with a new structure. There were no recommendations, however, for avoiding further capillary rise of moisture into the foundation or frost heave. If the real need for renovation and a more durable solution is greater, the structure will start to degrade again.

In terms of reducing heat loss, the negligible attention of consultants directed towards adding insulation to the foundation is troubling. As the foundation and ground floor junction is a typical location for a thermal bridge in detached houses, insulating the foundation is unavoidable for eliminating thermal bridge criticality (Kalamees, 2006) and achieving adequate energy-savings. While it is possible that insulating the foundation remains too overshadowed by other structures with larger surface areas, the desire to preserve the appearance of a natural stone foundation wall may be a factor among home-owners and consultants. This highlights the potential need for foundation renovation solutions, which would establish a compromise between energy performance and architectural appearance.

Floors

A need for partial or extensive renovation of floors was highlighted in 89 % of floor reports, consisting 38 % of all sample buildings. The most common floor structure was found to be either an outdoor air ventilated or non-ventilated wood floor with wooden beams, present in over 90 % of all floor reports. Other floor types included natural stone, concrete or earth floors, or were left unspecified. Most floors were from wood through the entire house (60 %), with a number of floors consisting of different materials in different rooms (wood and concrete; wood and earth; etc.).

The main floor damages and their causes

The most common damages of floors were related to material decay (31 %), sagging (22 %), or a general end of service life (6 %) (Fig. 3, Fig. 5 below). Problems related to the thermal comfort (such as low floor temperatures) of residents were occasionally highlighted as well. The common cause of material decay was excess moisture resulting in fungus growth, and insect damage. The leading causes of excess moisture were related to unventilated moisture evaporating from the ground and wooden beams or -boards in direct contact with damp soil.

Ventilation below the floor is crucial for removing excess moisture (either from evaporation from the ground or infiltration from external sources) from the beneath the floor and hindering the decay of wood elements (Burke, 2007). In Estonia, traditional floors were ventilated with regular openings within the foundation wall. 14 % of floor reports highlighted the existence of ventilation beneath the floorboards, with 34 % describing a lack of ventilation. Existing ventilation openings may have become blocked either intentionally or by accident due to rising ground levels. Another example of traditional, yet flawed floor design potentially leading to fungus growth would be leaving floor beams in direct contact with ground soil (Mattsson et al., 2010) and without ventilation, leaving the wood details in a perpetually moist environment.

Interior floor finishing acting as moisture barriers and trapping moisture against original wood boards, leading to fungus growth, were highlighted as a reason for damages. Floor moisture damages were occasionally also related to improper drainage around the building, which may direct rainwater against and through the foundation, creating localised points of material decay within the floor above. Sagging, resulting from loss of load capacity of floor beams, was also commonly correlated by consultants to material decay, although a few examples of improper construction methods, such as poor load bearing dimensions or spacing of floor beams were highlighted as reasons for sagging as well.

Poor design and lack of proper maintenance (such as not removing excess soil and not keeping ventilation openings open at correct times), leading to a lack of air exchange and wooden material in contact with damp soil, were the leading causes for nearly all wood floor damages.

Floor renovation recommendations by consultants

Two thirds of all floor reports include recommendations for a new floor structure, while the rest remain vague. The function of the building was a factor in determining recommended renovation extent, where house used only as summer residences received less extensive renovation advice when compared to dwellings used year-round. The removal of old, excess soil was crucial in all renovation solutions. Most reports also recommended reusing old original floorboards whenever possible. This poses risks, however, as this material will need to be inspected for fungal or insect infestation before re-instalment in renovated structures (Whittaker et al., 2021).

Recommendations for renovation works generally describe three options. Concrete slab on ground was the most commonly suggested solution (42 %), consisting of dry compacted subsoil, 100 to 200 mm of EPS or XPS insulation, a PE foil and a 70 mm concrete slab with floor heating (hydronic or electrical). An outdoor air ventilated floor on wooden beams was the second most common (23 %) renovation recommendation. Ensuring efficient ventilation between the floor and dry compacted subsoil was highlighted by consultants in order to avoid excess moisture due to evaporation from the ground. This solution poses risks, however, as without a ground covering or sufficient ventilation, rising relative humidity beneath the floor during warmer months might cause mould growth (Kurnitski & Matilainen, 2000). The third and least mentioned solution was an unventilated wooden floor, which described removing damaged floor beams and damp excess soil, building concrete pillars to support the wooden beams with a moisture barrier in between, and refilling the space with dry sand. This solution is likely to have the shortest service life and ought to not be recommended, as contact between soil and wood elements is still present and will likely lead to fungus growth (Mattsson et al., 2010).

Outdoor air ventilated wooden floor with crawl space has shown to be a risky structure because high relative humidity conditions below floor. A Latvian study on wood rot damages among 300 wooden buildings, including cultural monuments, found floors to be the most commonly affected structure, with fungal damage occurring in 43 % of all examined buildings (Irbe & Andersone, 2008). This is corroborated by the dissertation of Pirinen (2006), who studied the locations of damages in residential houses and found ground floors to be the most commonly damaged structure (35 % of examined buildings).

A lack of insulation is also likely to preserve low surface temperatures, leading to discomfort of residents during winter months. 67 % of floor reports recommended additional thermal insulation. In the case of outdoor air ventilated wood floors, increased insulation within the base floor decreases temperature and increases relative humidity within the foundation crawl space, causing a high-risk to wood structures with respect to mould growth (Bok et al., 2009; Sandberg & Samuelson, 2006). The risk of water entering the foundation crawl space due to difference in ground level between the crawl space and exterior ground remains as well, if land grading is not done to direct water from precipitations and snowmelt away from the building.

Although there are recommendations in the scientific literature (Matilainen & Kurnitski, 2003) to insulate the ground surface to increase the temperature in the crawl space and thereby reduce the relative humidity, or to cover the ground with coarse aggregates to reduce the capillarity of the ground, these measures were rather little recommended.

Constructing a concrete slab with adequate insulation thickness means digging deeper into the soil under the floor, which in certain cases can be hindered by low foundation depth and, in the case of an outdoor ventilated floor, water may spill under the floor because the ground level may become lower than the ground surrounding the building.

External wall and façade

Typical wooden log (round log or hewn smooth on the sides) external wall thickness was 12 to 18 cm. If walls were covered from external side, then mainly wooden boarding or in some cases brick veneer were used. From interior side, log was either not finished, covered by some board or plastered. Damage was either visually verified or suspected based on circumstantial factors. Load-bearing wood structures can be properly examined only after the removal of interior or exterior finishes, which may not have been possible during the consultation.

The main wall damages and their causes

A need for renovation or repair was highlighted among 94 % of all wall reports, constituting 77 % of all sample houses and the highest number among all other building structures. For log walls, physical damages can be generally described as either wood decay or sagging/shifting, appearing in 88 % of wall reports. Material decay (72 % of cases, followed by damage from insects 22 % of cases), was highlighted in 82 % of wall reports, establishing the most common type of damage among wooden log walls (Fig. 3, Fig. 4 & Fig. 6 above). The most common locations of material decay were found or suspected to be the lowest course of logs (47 %), followed by logs beneath window openings (19 %) and topmost courses of logs (12 %). In some cases, a wall in its entirety was found or suspected to be damaged (8 %). Less commonly, other parts of the log structure, like an outer corner, or a door or window buck were highlighted to be damaged as well. Damages from moisture or shifting logs matches findings from Finland, where log external walls of homes built before 1939 represent the most likely structure to be in risk of damages (Taylor et al., 2023).

The high vulnerability of bottom logs to wood rot growth was to be expected, as experience shows them to be the main points of rot damage in an external log wall (Austigard et al., 2014). Sources of excess moisture in these elements were found to be circumstantial, with upper log courses related to roof leaks and lower courses related to problematic foundations with insufficient plinth height (allowing precipitation water in contacts with logs), lack of a moisture barrier between the foundation and wood structure or lack of rainfall protection. Damaged log rows beneath windows were related to damaged or missing external windowsills, leading to rainwater infiltration at the window frame. Less common causes for decayed logs were related to insufficient facade finishing, lack of an air cavity between the wall and facade or foliage. Sagging or misplaced logs were highlighted in 35 % of wall reports, most commonly found or suspected of entire wall sections (11 %) or lower courses of logs (8 %).

Façade finishing or cladding (generally wooden boarding) was highlighted in 31 % of wall reports, with 19 % providing details concerning problematic technical condition. A number were described as damaged or deformed (10 %). Others described improperly installed newer finishing, either without a proper ventilation air cavity behind facade boarding, without a rainfall protector, without a rodent guard or left unfinished, thus exposing the wind barrier to the elements. Material decay of the log wall structure was rarely directly correlated by consultants to faulty façade finishing.

Wall renovation recommendations of consultants

Recommendations for renovation of external walls were broad. To eliminate sagging, either tie-logs or added support pillars within the structure were recommended. In some cases, interior log walls are recommended to be replaced with frame structures. Adding window bucks to so far unreinforced window openings was stressed as well. Logs with material decay generally all needed replacement, highlighted in 75 % of all wall reports. Depending on the extent of the damage, replacement may concern a single section of log, an entire log or an entire log course or wall section. When replacing lower courses of logs, replacing or adding moisture barriers between the foundation wall and wooden structure, including rainfall protector, were highlighted.

Recommendations for reducing heat loss appeared in 36 % of wall reports. The simplest solution was tightening the lateral grooves with traditional materials such as moss, wool or flax. To further airtight the building envelope, wind barrier membrane or boards are recommended to be placed beneath the exterior side of log (12 %). The most common wall additional insulation recommendation, present in 17 % of wall reports, was cellulose wool insulation between wooden frame, covered by a wind barrier. Thickness of insulation was rarely highlighted by consultants, with most hinting at using a thinner layer (for example, 75 mm) in order to preserve the building's architectural proportion. As insulating the external wall provides the highest potential for energy savings when compared to other structures (Alev et al., 2014), none of the aforementioned insulation solutions may be deemed acceptable for achieving an energy-efficient building stock (LTRS, 2020).

Windows and doors

Traditional windows were with two single-paned wooden frames (the interior frame was originally removed during warmer months). Original windows were seen as a valuable detail, deserving preservation and conservation. It was not uncommon for original windows to have been replaced with modern, multi-pane windows, which did not match the design of the originals. When windows were changed, either a new two frame 1+1 glazing solution, a new two frame 1+2 solution (where the interior frame has double glazing), or one frame window with double or triple glazing were typical solutions. Traditional door structures are wooden. The complete or partial survival of original doors was highlighted in 66 % of door reports.

The main window and door damages and their causes

A need for replacement or renovation of windows was highlighted for 95 % of all window reports, constituting 43 % of all sample buildings. The primary indicator for consultants when evaluating windows was originality (being present from the time of construction), present in 71 % of window reports. 35 % of window reports describe buildings with completely or partly surviving original windows, whereas the other 36 % describe buildings where all windows have been replaced during later periods.

Problems concerning original windows generally included material decay of the wooden frames and large air leakage through the window structure. 45 % of window reports highlighted a conservation potential for the existing windows (durability of frame), while 21 % were declared to be at the end of the window's service life and in need of immediate replacement. From experience of the authors, wood window frames can decay from use and climate load during its long use period and poor material quality and airtightness. Concerning the structure surrounding the windows, damaged or missing window bucks were highlighted (16 %), as either an oversight made during the time of construction or mistakes made during previous repair works (for example, widening existing windows or making new window openings). Missing bucks can lead to lower stability of the surrounding log wall. Windowsills were mentioned in 15 % of window reports, highlighted to be either damaged or missing (Fig. 3).

A need for renovation of doors was highlighted for 75 % of all door reports, constituting 15 % of all sample buildings. Damages concerning doors were generally material decay and worn finishes. Problems related to door bucks were occasionally highlighted as well, which were either missing, improperly installed or decayed, and had therefore led to sagging doorframes. Modern replacement doors were occasionally highlighted as being architecturally inappropriate for a traditional rural house.

Renovation recommendations of consultants

Recommendations for window renovation generally concern conservation of existing original windows and/or replacement with architecturally appropriate window designs with the goal of maintaining a historical appearance (95 %). Missing or damaged window bucks all needed to be installed or replaced before notable shifting of wall logs can take place. Missing or damaged windowsills needed replacement as well. The only recommendations concerning the reduction of heat loss included moving the window-frame outwards (window's and wind barriers surfaces are on the same line) when additionally insulating external walls, in order to avoid a "sunken" appearance and to minimise thermal bridge (24 %) in connection of wall and window. As the window-to-wall connection can indeed account for up to 40 % of heat loss across all thermal bridges within a building (Misiopecki et al., 2013), this recommendation is accurate. There was an oversight of window energy performance, however, which is troubling, considering that approximately 20 to 40 % of building heat loss can be attributed to a building's windows (Bülow-Hübe, 2001). Restoring original single- or two-paned windows is unlikely to achieve necessary energy savings. Therefore, modern window alternatives between conservation and complete replacement ought to be explored. It has been demonstrated that installing internal additional single- or double-glazed frames may offer comparable energy savings to complete window replacement under the right conditions (Litti et al., 2018). As energy-efficient windows were rarely recommended by consultants, there is a need for new alternative renovation solutions that would provide a satisfactory compromise between original details, architectural appearance and energy performance.

Recommendation for renovating doors generally highlighted conservation of original doors or replacement of architecturally inappropriate doors. Any damaged door bucks were recommended to be repaired.

Attic floors

All attic floors had a wooden load bearing structure with beams and ceiling boards. Traditional insulation material, such as including sand (22 %), sawdust (9 %), hay (5 %), mineral wool (4 %) and slack were placed between beams. The survival of original ceiling boards was highlighted among 43 % of ceiling reports.

The main damages and their causes of attic- and intermittent floors

A need for renovation of attic- and intermittent floors were highlighted in 74 % of all attic floor reports, constituting 34 % of all sample buildings. More than half of all attic floor were found to have moisture damage from roof leaks. In some cases, beams or undersides of ceiling boards may not have been visible during the consultation and therefore, their condition was not verified. This may explain why ceilings had the lowest percentage of verified renovation need when compared to other wood structures.

All cases of damage in attic floors were found to be related to physical damages, such as sagging (not enough load bearing capacity) (26%) or material decay (Fig. 4). Material decay was highlighted in 58 % of reports, related to either excess moisture and resulting fungus growth or insect damage. The specified cause for excess moisture was generally roof leaks.

Attic floor renovation recommendations of consultants

As attic floor damages were generally related to roof damages, existing roof leaks were recommended to be repaired. In some cases, as the beams may not have been visible during the consultation, further investigations were recommended after the removal of ceiling or floor structure. Following renovations were recommended: repairing, replacing or adding ceiling beams (16 %), removing decayed ceiling and attic floorboards (21 % of cases), adding framing to improve the load bearing capacity of existing walls or supporting ceiling beams (18 %).

To reduce heat loss, existing materials between beams were recommended to be removed and replaced with lighter and more efficient modern materials, such as cellulose insulation, supplemented by a wind barrier. With their study, La Fleur et al. (2019) showed that attic floor insulation is the most profitable insulation measure with a service life of 40 years.

Roofs

All roofs were high-pitched and with a wooden load bearing structure. The most common roof covering material among roof reports was found to be asbestos cement sheets (74 %), followed by metal sheet (14 %), wooden shingle (3 %) and reed (3 %). It was also common for an older traditional roof covering to be preserved beneath asbestos cement sheets added during the soviet period, such as reed, hay or shingle.

The main damages and their causes of roofs

The renovation need of roofs was highlighted for 92 % of roof reports, constituting 63 % of all sample buildings. Sagging (28%), material decay (57%) of the roof structure or roof covering, or missing rain gutter systems (18 %) were the most common roof renovation needs (Fig. 4, Fig. 6 below). The main cause was water infiltration from roof leaks or poor water tightness of flashing around penetrations like dormer, chimney, ventilation pipe, etc. The most common reasons for structural issues were faulty or damaged joints, broken rafters, rafters with insufficient dimensions or spacing, poor structural design, or demolition of load-bearing elements. A study of roof defects among Norwegian dwellings built between 1993 and 2003 highlighted leaky roof coverings or fittings as typical defect mechanisms (Gullbrekken et al., 2016). This is corroborated by another study of dry rot fungus prevalence in Norwegian buildings, where 94 % of material decay roof structures had been related to roof leaks (supplemeted by moisture seepage) (Austigard et al., 2014). These damages generally occur from precipitations and climate exposure, which are likely accompanied by lack of roof maintenance or improper construction methods applied during roof installation. For example, missing or damaged roof elements in the study included ridge boards, chimney flashes and valley flashes, which left the roof structure vulnerable to precipitations.

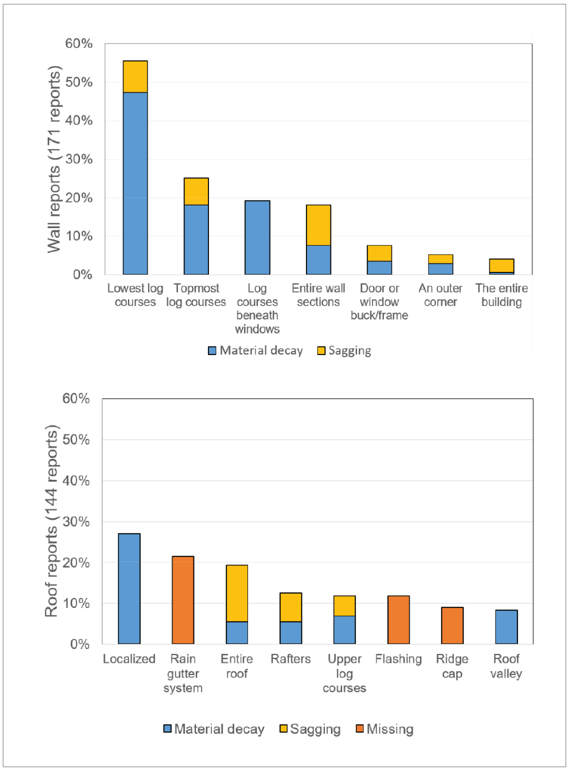


Fig. 6

Damaged or highlighted elements present in consultation reports concerning walls (above) and roofs (below)

The general condition of the roof covering was highlighted in 74 % of roof reports. A notable number and level of climate loads to roof material can lead to different types of damages, for example, sunlight can lead to brittleness of wood shingles, moisture can cause rust in metal sheets and biological growth can occur on mineral materials (Berdahl et al., 2008), such as asbestos sheets. A satisfactory, good or freshly installed condition of the roof covering was highlighted only for 19 % of roof reports. 55 % of roof coverings were generally declared to be at the end of their lifecycle and needing replacement. Old asbestos cement sheet roofs were mostly past their service-life.

Roof renovation recommendations of consultants

A third of roof structures were deemed salvageable by replacing or repairing damaged or missing rafters or collar beams (31 %). However, a number of roof structures were declared beyond repair and an entirely new structure was recommended in 17 % cases. There were also examples where new roof coverings had been installed on faulty structures. Other recommended works included installing or improving rain gutter systems (20 %), repairing or installing missing flashes (10 %), installing snow guards, or general cleaning.

Recommendation for insulating the roof in order to reduce heat loss were highlighted only in 13 % of roof reports. Ensuring proper ventilation below the roof covering was highlighted when insulating the roof structure and constructing heated rooms on the attic floor, as these structures become especially vulnerable to moisture damage (Gullbrekken et al., 2016). Insulation materials were often left unspecified. Minimising air leakage of insulated roof or attic floors was not recommended by consultants as a needed renovation measure, although its importance is shown in many previous studies (Domhagen & Wahlgren, 2017; Harderup & Arfvidsson, 2013; Roppel & Lawton, 2013). As roof can be considered more technically challenging, compared to external walls, foundations, or windows there is more room for errors when renovating. For this reason, consultants were likely more hesitant to provide specific recommendations, or preferred to recommend insulating the attic floor (recommendations for insulating the attic floor were three times more common than roofs), highlighting the need for training and improvement of technical education of consultants, as well as more comprehensible roof renovation solutions.

National renovation volumes resulting from estimated renovation need

Applying the aforementioned proportions of renovation need, estimates concerning quantity of damaged dwellings and volumes of construction materials necessary to eliminate these damages can be highlighted. According to Estonia's long-term strategy for building renovation, there are approximately 60 000 detached houses built before year 1945. The average percentage of wooden houses (both wooden log and frame structures) among these buildings is approximately 88% (Allikmaa, 2013), resulting in 53 000 wooden buildings. As the primary target group for the network of consultants are residents in lower-density and rural areas, dwellings in high-density cities, which form approximately 22% of the detached housing stock (LTRS, 2020), were excluded from the analysis, resulting in 41 000 wooden houses. The proportion between external walls with wooden log and timber frame structures among wooden houses in Estonia built before WWII is exactly not known. Within the database of consulted dwellings, 2% of wooden houses had a timber frame structure. In the current study, this proportion was referenced to exclude timber frame structures and estimate the number of log dwellings within the estimated sample, resulting in approximately 40 000 wooden log detached houses built before year 1945. As was previously highlighted, the highest possible number of barn-dwellings in Estonia is estimated to be 7000 (Lõuk, 2013). Considering the total number of log houses in lower-density areas in Estonia is approximately 40 000, the number of log wall detached houses is likely to be 33 000.

According to the results of this study, the expected number of log houses with damaged external walls (77% of sample dwellings) is approximately 31 000 (5500 barn-dwellings and 25 500 detached dwellings). Among these dwellings, approximately 3000 barn-dwellings and 14 000 detached houses (55% of damaged walls) can be expected to have notably decayed lower log courses. As damages may range in severity, the average volume of repair works is likely to involve (according to the experience of the authors) the replacement of the entire lowest log course. This would require, in total, 763 kilometres or between 8500 solid cubic metres to 19 000 solid cubic metres (assuming the average log diameter is between 120 mm to 180 mm) of replacement logs to repair these damages.

Conclusions

The total number of log houses with damaged roofs is approximately 25 000 (63% of sample houses), of which 4500 will require an entirely new roof structure due to critical damages (17% of damaged roofs). As 55% of roof reports highlighted roof coverings in critical need of immediate replacement, this will likely affect 14 000 log houses (2500 barn-dwellings and 11 500 detached houses), resulting in approximately 2 803 500 m^2 of new roof material in need of immediate installment.

A valuable database has been created based on building surveys conducted by the network of consultants initiated by the Estonian Open Air Museum's Centre of Rural Architecture. This database enables the determination of the technical state of houses, as well as current consulting and renovation practices. The current technical state provides insights into renovation needs from various perspectives, including load-bearing capacity, durability, hygrothermal performance, indoor climate (thermal comfort and indoor air quality), and energy performance. Analysis of the current consulting and renovation practices allows for the assessment of the durability and resilience of renovation measures. The findings and consultation reports identify problematic aspects that require further development in the counseling procedure as well as available renovation solutions, particularly in relation to achieving resilient, carbon-neutral, and healthy building stock.

According to the study, the most vulnerable building envelope structures among wooden log rural houses are external walls, roofs, and foundations. Excess moisture is identified as the main cause of damage to these vulnerable structures. Common sources of moisture include lack of ventilation, moist air, rainwater infiltration, and capillary moisture. Among stone structures such as foundations and chimneys, cracks in the masonry and erosion of mortar joints are prevalent issues. Renovation needs for these structures generally involve ensuring safety and extending the service life of building structures by repairing immediate damages and addressing the root causes of the damage. The renovation needs of the wooden houses indicated in the study could be scaled to the level of the entire building stock, which made it possible to estimate the renovation volumes required for the renovation strategy action plan at the national level.

The reports highlight damages that are generally caused by poor design, construction, or maintenance practices, as well as natural weathering over time. As many renovations in the studied houses are carried out by occupants or individuals without formal construction qualifications, it is imperative to have detailed design documentation or problem-based typical renovation solutions (including technical drawings/models with descriptions) for the most common renovation needs, linked to the building renovation passport. This approach provides renovation solutions with proven performance and minimizes time wasted on discussing materials and renovation approaches with builders. Given the anticipated increase in the need for deep renovations of houses in the coming decades, it is necessary to have a larger pool of qualified workers in this field or to educate homeowners to a level where they can undertake simpler renovation tasks themselves. For the majority of consultation cases examined in this study, the involvement of a specialist only occurred after a building structure had already been damaged. This implies that the primary focus is often on eliminating immediate damages before addressing the reduction of heat loss. Consequently, there is an increase in overall workload, cost, and time spent on renovating dwellings compared to structures in good or satisfactory condition. This underscores the necessity of involving specialists in maintenance and renovation prior to the occurrence of noticeable damages. The varying levels of education and work experience among consultants further accentuate the need for training to ensure that their recommendations are on par with those provided by specialists in the field.

The renovation solutions proposed by consultants to improve energy performance, indoor climate, and moisture safety were generally inadequate in achieving decarbonized, healthy, and long-lasting building stock. The renovation of technical service systems was rarely highlighted, under-utilizing the potential for improving both indoor climate and building energy efficiency, as well as reducing the indoor moisture load on wood structures. Most successful renovations occur when energy performance and indoor climate enhancement renovations are carried out concurrently with necessary “anyway” renovations. This synchronized approach not only results in reduced overall costs, but also enhances the ultimate quality of the renovation project. Given the interconnectedness of structural elements and the potential for damage transfer, it is crucial that renovation works be planned holistically, considering the building as a whole over an extended period of time.

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