Sustainable Management of Historic Rural Churches

THE FINAL RESEARCH REPORT

of the project

'Sustainable Management of Historic Rural Churches in the Baltic Sea Region (SMC)'

Tallinn-Visby, 2013

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SUMMARY

Medieval churches were originally unheated and indoor climate of the church was mainly determined by the outdoor climate. Microclimate is an essential factor for the use and long term physical preservation of the buildings and the valuable artefacts housed in them. The present situation generates numerous problems with the physical structure and the microclimate of these buildings. This report summaries researchon in project to improve the climatic conditions, performance and durability of structures and interior items, and energy efficiency of churches.

Indoor climate conditions were analysed in ten Estonian and Swedish churches in order to get an overview of the present situation and find solutions to problems and risks that need to be reduced. In Estonian churches, the average indoor temperature in summer was 15.4 °C and in winter, -1.0 °C and average relative humidity in summer was 87% and in winter 88%. Most of the time, indoor RH in investigated churches is higher than outdoors due to higher moisture content caused by the drying massive walls. A high level of relative humidity in Estonian creates a significant risk of mould growth. Average probability of all investigated churches conditions facilitating mould growth was 53% or in the range of 45%...59%. Mechanical degradation of indoor objects is manly caused by fluctuations in relative humidity. In this study, irreversible damage risk of wooden objects and cracking risk of the gesso layer of panel paintings due to RH fluctuations was investigated. Results showed that there are only a few percent of the measurement result cross the critical line in unheated Estonian churches. Conditions facilitating irreversible response in wooden sculpture are in the range of 0…1.6% of the yearly measurement results. The analysis of the cracking risk of the gesso layer showed that conditions exceed the critical line only in one church where repair works took place that played an important role in RH fluctuations.

Air leakage was measured using the fan pressurization test and the tracer gas technique. Average air leakage rate at 50 pascals q_{50} was 12.3 $m^3/(h \cdot m^2)$ with a maximum value of 23 $m^3/(h \cdot m^2)$ and a minimum value of 6.8 $m^3/(h \cdot m^2)$. Results of air exchange rate per hour were 0.6 ach, 0.3 ach and 0.3 ach, respectively. The results showed that small differences between indoor and outdoor temperature do not influence air infiltration very much. Main leakage sites were holes and gaps in arches, broken window panes and cracks around doors.

Algal growth and pink coloration due to specific bacteria occurred massively in the studied medieval churches In Estonia. It seems that algal growth is stable but areas with pink coloration are getting larger. Mould growth is mainly visible only where organic substances are available (linseed primer, paints). Nevertheless, mould is spread more widely if looking inside plaster and between paint layers under the microscope. Wood rot is a severe problem in Valjala Church and the infected floor area is constantly growing. In order to protect stonework from the harmful impact of chemically active rain, a process called “hydrophobization” is used, involving agents that prevent moisture from being absorbed by stone. A multidisciplinary approach is important when studying microbial impact on building materials. It is necessary to integrate different concepts in order to determine the mechanisms of deterioration as well as methods of control.

An in situ study of plaster/render and finishing layers was carried out from May to September 2012 at Pöide Church. A total of 12 different types of plaster/render were found on the walls and vaults of Pöide Church, dating from the 13th to 19th century. The laboratory results show that the composition of ancient plaster mortar from Pöide Church was 1:2.2 (the ratio of lime binder (including indissoluble limestone, clay etc.) to aggregate). The condition of plaster and render at Pöide Church is poor. Damage found include: detached layers, loose and damaged surfaces, hardened surfaces. These damages are mostly related to excessive moisture.

The laboratory analysis of lime mortars made with different aggregates showed the improvement of the obtained characteristics. Adhesion strength of fine sand mortars exceeds the adhesion strength of coarse sand mortars and increasing the amount of lime binder improves adhesion strength. Increasing the relative amount of aggregate in the mortar causes an increase of density of mortar, addition of ground chamotte decreases the density of mortar, use of coarse sand and ground chamotte decreases the density of the mortar. The sets of tested lime mortars show basically identical capillary water absorption in hardened mortar while water absorption is lowered to certain extent by decreasing the content of sand. Ancient plaster mortar had the lowest water vapour permeability; its water vapour diffusion resistance factor was the lowest. Water vapour diffusion resistance factor is increased if the ground chamotte with proper size fractions is added to the aggregate mix. Frost resistance of the lime mortars was low.

Mapping moisture content of walls by means of microwave reflection is a sensitive and very suitable method for diagnosing moisture problems of buildings being part of national heritage. Graphically presented results are easily readable even for a non-specialist and significantly facilitate the analysis of the problem. Measurements carried out in churches in Saaremaa show that the main source of moisture in churches included in the present study is water condensing on walls in late spring–early summer. This common problem on all unheated churches was confirmed by analysis of dynamics of moisture content of walls. Significantly higher moisture content can be observed in parts of walls where outer protective structures and joints are damaged. Rain water leaking into walls shifts the maximum of seasonal moisture content to summer or even later. Another source of moisture for all churches included in the present study is moisture accumulating from the ground through capillary forces. To minimise moisture problems in churches, the building envelope of the church should be repaired / kept in good conditions; churches should be equipped with rain water systems (gutter with tubing carrying the accumulated water further away); air-tightness of doors and windows should be improved; adaptiove ventilation for air change could be used, especially in the spring–summer period.

The indoor climate of a majority of Estonian medieval churches without climatization is too humid ; therefore, a necessity exists for climate control systems to ensure better conservation of the artworks and structures of the churches. In the climate control system test period where dehumidification and air-to-air heat pumps were used, relative humidity immediately decreased while the systems were operating. Because the dehumidification devices were installed separately in different locations in the church and with better airflow distribution, the dehumidifiers could keep the intended parameters better throughout the church. With the system pre-set to 75%, relative humidity was 70…75% everywhere throughout the church. With an air-to-air heat pump, relative humidity in the hall is kept inside the permitted and desired limits but in the choir room and in the sacristy, it was higher than in the hall, this because both indoor units were installed in the hall and the airflow was insufficient to increase the temperature. Based on measurements and simulations in Risti church adaptive ventilation did not guarantee stable relative humidity indoors because the system is less controllable. The most energy efficient for Risti church of all climate control measures is the conservation heating with air-to-air heat pump with an energy consumption of 23 kWh/m^2 per year to ensure a relative humidity of 70%. The energy consumption of rotary dehumidification is 58 kWh/m^2 per year to ensure the same 70% indoor relative humidity. The most energy consuming is direct heating with an energy consumption of 85 kWh/m^2 per year to ensure a relative humidity of 70% indoors. Dehumidification similarly energy consuming with direct heating at higher relative humidity, 85…90%. Adaptive ventilation with direct heating is the most energy consuming. This is due to the fact that with adaptive ventilation, you have to heat up the outside air while conservation heating heats up only indoor air.

There are different climate control strategies for churches, which are used occasionally. The aim is to avoid biological degradation, so the set point and the allowable variation for RH is the important parameter. The energy consumption should be minimized to ensure a sustainable solution. Passive climate control is in general not sufficient to prevent biological degradation. Never the less, in some unheated churches the interiors have survived for centuries in a humid environment without any climate control. This is possibly due to the low temperature in winter. Conservation heating should only be implemented if at the same time there is a need for human comfort. This is relevant for churches, which are used once in the week or more, and therefore needs intermittent heating. A heat pump is particularly efficient for conservation heating, because it performs well with a small temperature difference. Dehumidification is generally more energy efficient than conservation heating. A condensation dehumidifier is useful in summer, when the temperature is above 10 °C, or in combination with moderate heating in winter. A sorption dehumidifier is to prefer if the church is not heated, because it works at low temperatures. Adaptive ventilation can possibly be used to keep the RH below the limit for mould growth or avoid condensation on cold walls or floor. It is particularly efficient for buildings with an internal source of humidity. In combination with a low infiltration rate, this method is the most energy efficient strategy. In addition to the technical requirements, the climate control solutions for churches need to be robust and reliable as resources for maintenance are limited. Also the installations must not interfere with the use of the churches and the visual and physical impact should be minimized.

1 EESTI UURITUD KIRIKUTE EHITUSTEHNILINE SEISUND

Paul Klõšeiko, Targo Kalamees

1.1 Sissejuhatus

Käesoleva uuringu käigus tuli esile ilmekalt Eesti maakirikute halb ehitustehniline seisukord. Probleeme oli palju ja nende eraldi väljatoonimine selgus olevat hädavajalik. Seetõttu tehti uuritud kirikutes ka üldise ehitustehnilise seisundi ülevaade. Selle peamine eesmärk on strateegiliste suundade seadmiseks vajalike tüüpsete vigade ja nende põhjuste väljaselgitamine.

Käesolev ülevaade on tehtud Eesti kirikute baasil ja peamiselt Eesti lugejale, mistõttu on tekst ka eestikeelne.

1.2 Meetodid

Tehnilise seisundi hindamiseks kasutati järgmisi meetodeid:

- arhiiviandmete ja varasemate uuringute analüüs;
- kirikuhoonete käesoleva hetke tehnilise seisundi hinnang ja põhiprobleemide analüüs;
- suulised intervjuud restauraatorite ja haldajatega.

Tehnilise seisundi hindamise käigus täideti spetsiaalselt koostatud ankeet, kus hinnati hooneosade tehnilist seisukorda vundamendist kuni katuseni, samuti fotografeeriti kahjustatud hooneosi põhjalikult.

1.3 Uuritud kirikute ehitustehniline olukord

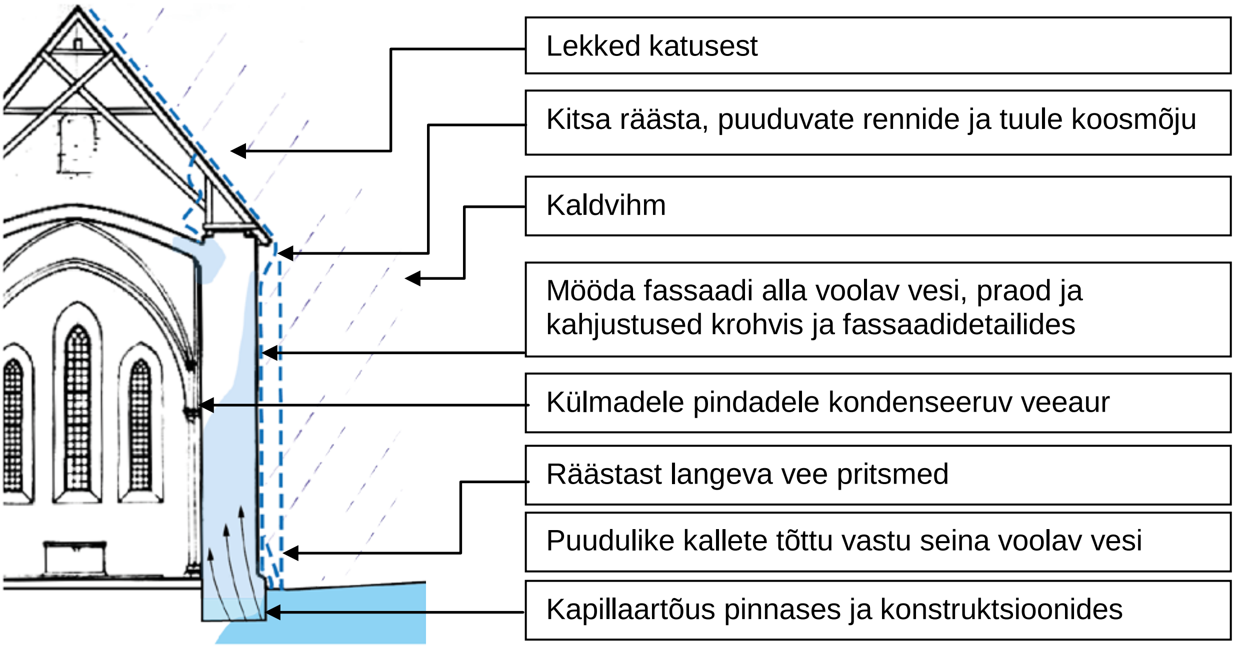
1.3.1 Üldist

Tinglikult võib jaotada hoonete tehnilist seisundit mõjutavad tegurid jaotada järgmiselt:

- Sise- ja väliskliimatingimustest põhjustatud peamised puudused:
  - Külmumis-sulamistsüklite tõttu toimuv lagunemismehhanism märgunud konstruktsioonides;
  - Reguleerimata sisekliimast peamiselt liigniiske ja alajahtunud olukord kirikus;
  - Veeauru konderseedumine tarindi pindadel ja sees;
  - Mikrobioloogilised kahjustused (seen, bakter, vetikas jms.);
  - Metallide korrosioon;
  - Soolkahjustused;
  - Putkkahjustused.
- Füüsilistest mõjutajatest põhjustatud puudused:
  - Konstruktsioonide ebaühtlastest vajumiste st põhjustatud deformatsioonid ja praod ning nendest tingitud konstruktiivse skeemi muutumine ja kandevõime vähenemine;
  - Tormikahjustused jms.

Reaalselt esinevad mitmed neist koos, olles tihtipeale laia (koos)mõjuga ning põhjustades täiendavaid kahjustusi ka teistele hooneosadele. Nt. ebaühtlaste vajumiste mõju ulatub võlvideni ja võib põhjustada varinguid, samuti on puudulike või kahjustatud vihmaveesüsteemide tagajärjed nii fassaadide lagunemine kui sool- ja vetikakahjustused siseruumides. Et suur osa probleeme on seotud kõrge niiskuse ja märgade konstruktsioonidega, annab põhilised viisid, mil moel liigniiskus tarinditesse jõuab, Joonis 1.1. Lisaks eelnevale on oluline roll hoone haldajal, kelle tegevusest sõltub puuduste edasine areng ja hoone käekäik.

Selle peatüki järgnevates jaotustes on esitatud uuritud kirikute tehnilise seisundi üldine kirjeldus, puuduste ja nende tekkepõhjuste analüüs ning nende võimalikud kõrvaldamis- ja vältimismeetmed.



Joonis 1.1 Konstruktsioonide märgumise näitlik skeem (alusjoonis: Kaarma kiriku mõõtmisjoonised, Lõige A-B (idast), Muinsuskaitseameti arhiiv, säilik P-195).

1.3.2 Vundament ja sokkel

Uuritud kirikud olid kirikud rajatud lintvundamendile, mis on peamiselt konstruktsiooniliselt samasuguse lahendusega nagu välisseinadki: harilikult looduskivimüüritised lubimördil, kuigi alumistes vundamendikihtides ei pruugi olla kasutatud sideainet. Varasemaid uuringuid analüüsides selgub, et vundamente ei pruugitud rajada (vähemalt mitte terviklikult) tugevatele pinnasekihtidele vaid ka nõrgemale pinnasele, samuti esines täitepinnase kasutamine sobivate pinnavormide andmiseks. Ebaühtlase tugevuse ja deformatsioonimooduliga pinnasekihid vundamendi all tingivad ebaühtlasi vajumisi, mis omakorda põhjustavad pragude teket hoone konstruktsioonides. Hoonete rajamisest tingitud deformatsioonid on tänaseks peamiselt lakanud ja kahjustused parandatud, samas läbi aegade teostatud mahukad juurdeehitused (uued hoonemahud, kontraforsside laiendamine jms) on täiendavaks koormuseks pinnasele ning hilisemate vajumiste mõju võib veel tänapäevalgi ilmne olla.

Hoone rajamisega võrreldes on pinnasekõrgus hoone ümber tõusnud (vt. Joonis 1.2 paremal). Nii huumusetekkest, kirikuaeda matmistest kui ka räästast langeva vee erodeeriva mõju tõttu on pinnase kalded hoone ümber aja jooksul kadunud või muutunud rohkem hoone poole kaldu (Joonis 1.2 vasakul). Hüdroisolatsiooni puudumine, niiskesse pinnasesse ulatuv krohv, vuugimört ja poorsed müürikivid võimaldavad kapillaartõusu, mille tõttu liigub vesi konstruktsioonis ka veega otseses kontaktis olevast pinnast kõrgemale. Kõrgem pinnasetase ja hoone poole olevad kalded tähendavad suuremat soklitele ning seintele mõjuvat niiskuskoormust (vt. Joonis 1.1) – tagajärjeks kiirendatud lagunemine ning probleemid vetikate, soolade ja hallitusega (vt. ka jaotused 1.3.3.2 ja 1.3.3.3). Lahenduseks on hüdroisolatsiooni rajamine, hooneümbruse kallete korrastamine, sademevee korraldatud ärajuhtimine (vt. ka Joonis 1.3) ning vajadusel drenaažisüsteemi rajamine.

Probleemne ehitusdetail on ka katmata, etteulatuvad müüriosad, mida eriti soklite juures esinev rohkesti. Etteastega soklitel peab horisontaalselt osalt vee ära juhtimiseks olema piisav kalle (vähemalt 1:5) ning karniis, samuti peab kaldekihi materjal olema vähese veeimavusega. Kõigil kirikuhoonetel polnud need nõuded täidetud (vt. Joonis 1.4 vasakul) – see suurendab seinte niiskuskoormust ning põhjustab materjali enneaegset purunemist kui niiskuskahjustusi. Taimestik tuleb potentsiaalselt lagundava mõju ja täiendava veekoormuse vältimiseks eemaldada. Hüdrofobiseerivad pinnakatted võivad samuti veekoormuse vähendamisel abiks olla, aga nende mõju tuleks enne kasutamist täiendavalt hinnata.

Joonis 1.2 Vasakul: hooneümbruse pinnase kalle on kiriku poole ja juhib täiendavat vett välisseina äärde.
Paremal: pinnase kõrgus hoone ümber on aja jooksul tõusnud, millega kaasneb ka tõenäoline niiskuskoormuse kasv seinatarindile.

Joonis 1.3 Vasakul: vihmaveerennita räästast langev vesi märgab soklit, pinnaselt seinale pritsiv märg huumusekiht aitab kaasa määrdumisele, vetikate kasvule ja külmakindluse langemisele.
Paremal: vihmavee ohutu hoonest eemale juhtimine on sokli eluea ja niiskuskahjustuste vältimise osas kriitiline, abiks on nii sobivad pinnasekalded kui spetsiaalsed rennid.

Joonis 1.4 Vasakul: etteastega soklil peab vee ärajuhtimiseks olema piisav kalle ning karniis; pildil olev sokkel on olnud sambla ja taimekasvuks piisavalt niiske, kiirendades seeläbi konstruktsiooni lagunemist ja niiskusest tingitud probleeme veelgi.
Paremal: müüritise, kus keskmine täidiskiht pole sideainega seotud, võib ühe väliskihi lagunemine viia varisemisohtlikku seisu.

Joonis 1.5 Sokli ja vundamendi kaitseks ehitatud kaitsekatus. Töid pole lõpuni viidud: süvendist ja hoone ümbrusest vee eelmalejuhtimine on lahendamata.

1.3.3 Seinad

1.3.3.1 Kandekonstruktsioon

Seinte tüüpiliseks konstruktsiooniks oli lubimördist vuukidega pae- ja/või maakivimüüritis. Seinu uuringu käigus ei avatud ning projekti lühikese kestvuse tõttu pragude arengut ei jälgitud.

Peamiselt olid nähtavad, erineva pikkuse ja avanemisega praod põhjustatud tõenäoliselt ebaühtlasest vajumisest. Juhtudel, kui müüritise täidiskiht on laotud ilma sideaineta, võib väliskihtide lagunemise tagajärjeks olla müüritise kandevõime ammendumine ja varing (vt. Joonis 1.4 paremal ja Joonis 1.8), mis võib edasi kanduda ka deformatsioonide suhtes tundlikele laekonstruktsioonidele. Väliskihtide lagunemisel on roll eelkõige nii ilmastikul (vt. jaotus 1.3.3.2) kui ebaühtlastel vajumistel (vt. jaotus 1.3.2).

1.3.3.2 Fassaad

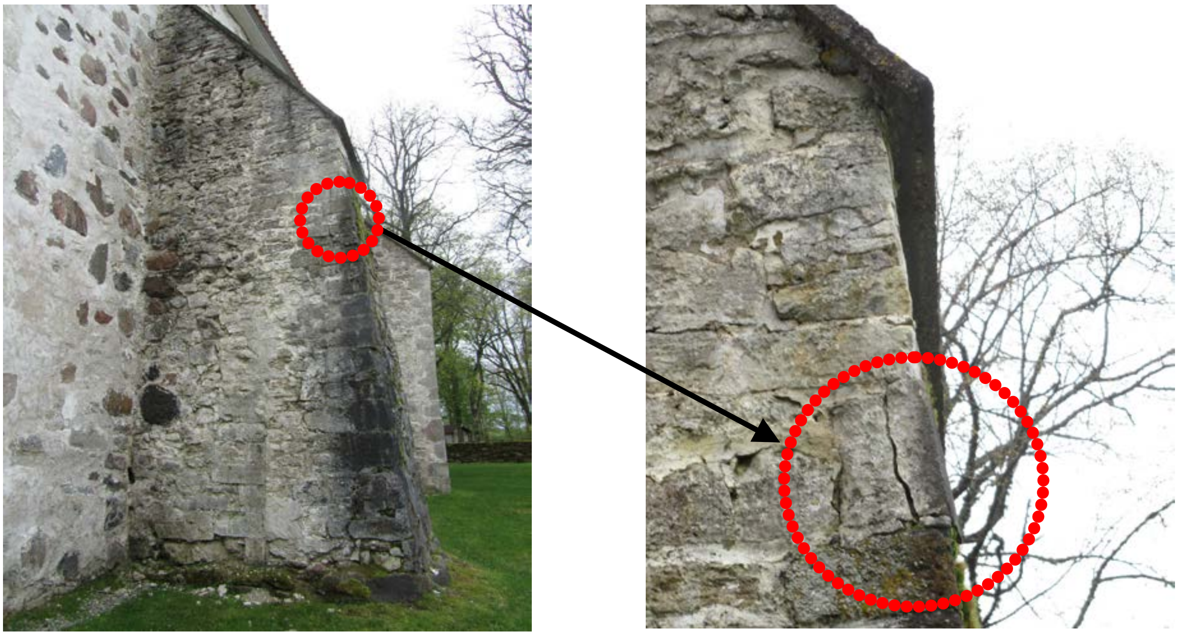
Uuritud kirikute fassaadid olid kaetud lubikrohvi ja –värviga, esines ka krohvimata pae- ja maakivist seinaosasid (nii suurematel pindadel kui ka dekoratiivselt nt. nurkades). Katmata raidkividetailid olid kasutusel nt. karniisidena, aknalaudade ja –raamide ja portaalidena, samuti ka soklil.

Enamikul uuritud kirikute fassaadidel esines suuri väga halvas tehnilises seisus alasid. Kahjustustel oli otsene seos suure veekoormusega tingituna nt. lühikestest või puuduvatest räästastest, puudulikest vihmaveesüsteemidest (vt. jaotus 1.3.7), puuduvatest/vigastest veeplekkidest/kividest (Joonis 1.10), purunenud ja lekkivatest karniisidest (Joonis 1.9 paremal) jms. Pragunenud ja pudenenud krohvi kaudu jõuab vesi müüritisse ja krohvikihi taha ning ülejäänud seina kahjustumine kiireneb. Kulukate ja töömahukate tagajärgede vältimiseks tuleks fassaadisüsteemi kahjustused kõrvaldada, sama kehtib ka kahjustatud karniisidele, aknalaudadele jms detailidele. Korras fassaadil on probleemid paremini märgatavad ning on võimalik tekkivatele kahjustustele kiirelt reageerida.

Lisaks veekoormusele on osaliselt põhjuseks ka lubikrohvi tugevus – parandusteks kasutatud krohvide koostis võib olla antud tingimustesse mittesobiv või ebakvaliteetne. Liiga jäigad krohvid või vale paigaldusejärgne hooldus võivad tekitada pragusid või irdumist esialgsest seinast ning vee sattudes tarindisse ka selle lagunemist. Liiga nõrk krohv on rasketes ilmastikutingimustes liiga lühikese elueaga. Liiga aurutihe krohv põhjustab vee kogunemise krohvikihi taha ning seal külmudes krohvikihi irdumist ja seina lagunemist. Ilmneda võib ka seina ja krohvikihivaheline soolade kristalliseerumine, mille tagajärjeks krohvi irdumine.

Fassaadikrohvi jätkuva lagunemise põhjuskeks lisaks suurele keskkonnakoormusele võib olla ka puudulik tehniline teadmine restaureerimisel kasutatavate krohvide omadustest ja kestvusest. Sageli on krohviretseptides esitatud kogused ebamääraselt või ligikaudselt, puudu vajalik veekogus jne. Seetõttu on selles vallas vaja oluliselt rohkem uuringuid, et vältida liigset vigadest õppimist. Vigadest õppimine on liiga ressursimahukas (aeg, raha, professionaalsete inimeste olemasolu jne.) ning nii väärtuslikel hoonetel ka hoone väärtust kahjustav.

Joonis 1.6 Kontraforssidel on küll katus peal, aga liiga lühikese ülekattega seinale, mistõttu sealt langeb vesi otse seinale. Sein on märg, millele viitab samba intensiivseim kasv selles osas, mis on räästa üleulatusest väljaspool.



Joonis 1.7 Kontraforssi valgunud vesi on külmudes lõhestanud kivi.

Joonis 1.8 Kontraforssidesse valgunud vesi on viinud müüritise lagunemiseni.

Joonis 1.9 Vasakul: krohvi eluea ammendumist kiirendavad näiteks liigne veekoormus. Paremal: raidkivikarniisi liitekohad on hüdroisoleerimata ning vesi jõuab fassaadile.

Joonis 1.10 Vasakul: mördist aknaplaat pole sadevett fassaadist ohutult eemale juhtinud. Paremal: raidkivist aknaplaadid ulatuvad küll fassaadist üle, kuid plaatide liitekoht võimaldab veel müüritiseni jõuda, samuti on probleemsed servad.

Joonis 1.11 Krohvi kahjustuste kaudu konstruktsiooni tungiv vihm ja lumi põhjustavad külmudes seina lagunemise.

1.3.3.3 Seinte sisepind

Seinte sisepinnad olid sarnaselt välispinnaga tüüpiliselt kaetud lubikrohviga ning –värviga.

Seinte sisepinnal olid põhilisteks probleemideks nii seente, bakterite, vetikate kui soolade põhjustatud kahjustused. See on viiteks seinte suurele niiskussisaldusele. Vetikate kasv (Joonis 1.12 vasakul) küll otseselt konstruktsioonide kandevõimet ei kahjusta, kuid rikub krohvimaalinguid ja ilmet. Restaureeritud/konserveeritud seinale ilmub kahjustus, ilma probleemi tekkepõhjust kõrvaldamata, mõne aja pärast tagasi.

Peamised soolakahjustused on seotud soolade kristalliseerumisega (vt. Joonis 1.12 paremal, Joonis 1.13). Kui seinatarindi kihid on sarnaste niiskustehniliste omadustega, võib see aset leida pinna peal. Kristalliseerudes suureneb soolade maht ning krohvikiht eraldub seinast ja lõpuks ka pudeneb. Et soolade migratsiooni ning bakterite, hallituse ja vetikate kasvu vältida, tuleks hoiduda seinakonstruktsiooni täiendavast märgumisest (vt. jaotised 1.3.3.2, 1.3.7), samuti on tähtis hoone sisekliima (eelkõige niiskus ja temperatuur) sobivas vahemikus hoidmine.

Niisked seinad on ohuks ka neile toetuvatele puidust taladele (vt. Joonis 1.15 vasakul) ja arhitektuursetele elementidele (vt. Joonis 1.17) ning roostetavast terasest detailidele (vt. Joonis 1.15 paremal). Puittalade seinaga kokkupuutuvad pinnad peaksid olema kaetud hüdroisolatsiooniga. Roostetava terase puhul tuleb kasutada kaitsekihti või projekteerida keskkonda sobiva korrosioonikindlusega.

Esines kirikuid, kus esteetilistel kaalutlustel oli seinte sisepinnale lisatud täiendav laudisekiht. Niiske seina ette puitlaudise paigaldamine tõstab müüritise ja laudisevahelise õhu niiskusetaseme kõrgeks ning tekib hallituse- ja mädanikuoht (vt. Joonis 1.14). Lisaks laudise enese lagunemisele on ebasoodsas seisus ka laudisega kokkupuutuvad vahelae- või rõdutalad (vt. Joonis 1.15 vasakul) – ohtu satuvad ka kandekonstruktsioonid.

Seinte niiskussisalduste mõõtmised mikrolainemeetodil (vt. pt 7) näitasid, et kevadel ja varasuvel seintele kondenseeruval veeaurul on seinte märgumisel oluline roll. Peamiselt on see põhjustatud talvel kütmata kirikute madalast temperatuurist kevadel, kui välisõhu veeaurusisaldus on suurem siseõhu küllastussisaldusest (vt. Joonis 1.16). Olukorda saaks parandada nt. konserveerimisküttega, mis väldiks temperatuuri liigset langemist talvel ja kiirendaks tarindite ülessoojenemist ning vähendaks või väldiks perioodi, millal kondenseerumine ja kõrge pinnaniiskus võimalikud on või mehaanilise kuivatusega. Samuti on nii kahjustustele kui mõõtmistulemustele tuginedes võimalik üheselt osutada nii müüritises toimuva kapillaartõusu kui välisseinale jõudva vee mõjule kõrgete sisepinna niiskustasemete kujunemisel.

Joonis 1.12 Vasakul: vetikakasv on viiteks seina pinna kõrgele niiskussisaldusele.
Paremal: Soolad võivad kristalliseeruda nii krohvi/värvikihi all kui selle pinnal.

Joonis 1.13 Soolkahjustused välisseina sisepinnal.

Joonis 1.14 Hävinud laudis seina sisepinnal: niiske kivisein on olnud seest poolt kaetud puitlaudisega, seina ja laudise vahel tekivad sel juhul sobivad tingimused hallitus- ja mädanikseente kasvuks.

Joonis 1.15 Vasakul: Seinale toetuv rõdutala on niiske seina tõttu muutunud soodsaks kasvukohaks mädanikseentele, protsessi on kiirendanud ka seinte sisepinda katnud laudis.
Paremal: Kaitsmata roostetava terase või raua puhul esineb kontaktis niiske seinaga korrosioon.

Joonis 1.16 Madala temperatuuriga pindadele kondenseeruv veeaur on oluline tegur tarindite märgumisel (eelkõige kevad-suvisel perioodil ülessoojenemata kirikute ventileerimise tõttu). Vasakul: punase ringiga tähistatud kondensaat avatud kirikuukse ees. Paremal: kondensaadipiisad vetikaga kaetud seinapinnal.

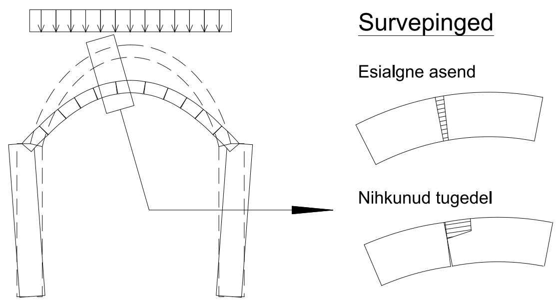
Joonis 1.17 Niiskes kiviseinas olev puitkapp on potentsiaalne koht hallituse tekkeks. Halvimal juhul hakkab arenema puitu lagundav mädanikseen.

1.3.4 Laed/võlvid

Kirikute konstruktsiooni üheks oluliseks osaks on laed – võlvitud kivikonstruktsioonina rajatuna on nad äärmiselt tundlikud ebaühtlaste vajumiste ja seinte asendi suhtes. Kui võlvide toed nihkuvad (s.t. sille suureneb), väheneb kivide omavaheline kokkupuutepind, survepinged kasvavad ning kandevõime võib ammenduda. Enne lõplikku varingut võib laest hakata ka müüritise tükke kukkuma, mis on samuti ohuks allviibijatele (vt. Joonis 1.18 vasakul).

Uuritud kirikute puhul oli esinenud erinevaid ümberehitusi, mis osalt olid tingitud võlvide pragunemisest ja varinguhirmust, teisalt aga ka põhjustasid täiendavaid vajumisi – nt. massiivsete kontraforsside rajamine on täiendavaks koormaks vundamentidele. Samuti oli teostatud võlvide fikseerimist teras- ja puittõmbidega.

Igal juhul on pragude ja võlvide kujupüsivuse osas tähtis pikaajaline jälgimine (nt. kipsmajakate ja reeperitega) ning vajadusel otsustav sekkumine.

Joonis 1.18 Vasakul: võlvidesse on tekkinud praod, kukkuv krohv ja kivid on ohuks allviibijatele, deformatsioonide edasi arenedes võib variseda ka terve lagi.
Paremal: võlvi tööskeem - kui võlvi toed on esialgsest asendist (kriipsjoon) nihkunud, väheneb kivide kokkupuutepind (survetsoon) ning sama koormuse vastuvõtmiseks kasvavad survepinged ja tugedele mõjuv horisontaalkoormus. Materjali purunedes arenevad deformatsioonid edasi kuni konstruktsiooni varisemiseni.

Joonis 1.19 Vasakul: Vasakul: võlvlagede konstruktsiooni on täiendavate deformatsioonide vähendamiseks tugevdatud tõmbidega.
Paremal: Võlvikiirdis võlviroiete ebasümmeetriline ühendumine

1.3.5 Avatäited

Uuritud hoonetel olid enamus juhtudel ühekordse klaasinguga aknad, raamide materjaliks oli kasutatud nii raidkivi, puitu kui metalli.

Avatäidete õhutihedus oli silmagagi märgatavalt madal (vt. Joonis 1.20 kuni Joonis 1.22) – praod ja avaused raami ning piirneva konstruktsiooni vahel on niivõrd suured. Ühest küljest võib seda pidada osaks ventilatsioonisüsteemist, teisalt kui soovida saada sisekliima üle suuremat kontrolli ja vähendada niiskete ilmadega ventilatsiooniõhuga hoonesse kanduvat vett (nt. kuivatuse, juhitava ventilatsiooni ja/või konserveerimiskütte näol), tuleks õhupidavusele rohkem tähelepanu pöörata.

Akende madalast soojapidavusest tingituna toimub õhus oleva veeauru kondenseerumine madala sisepinnatemperatuuriga raamidele ja klaasidele. Niiske keskkond on sobiv kasvukeskkond vetikatele ja põhjustab kuivades ka soolade väljakristalliseerumist – vt. Joonis 1.22.

Üks võimalikke akende renoveerimislahendusi on olemasolevale aknale lisada välispinda kaasaegne klaaspakett (vt. Joonis 1.23). Nõnda on tagatud akna soojapidavus ning õhutihedus ja samas on ka esialgne aken seest takistusteta vaadeldav.

Joonis 1.20 Avatäidete õhutihedus on silmaga nähtavalt madal.

Joonis 1.21 Lume tungimine siseruumidesse madala õhutiheduse tõttu. Lume sulades konstruktsioon märgub.

Joonis 1.22 Akna läbijooksu ja pinnakondensaadi tagajärg välisseina sisepinnal.

Joonis 1.23 Väljastpoolt klaaspaketiga kaitstud aknavitraaž tagab akna soojapidavuse ja õhutiheduse.

1.3.6 Katus

1.3.6.1 Katusekate

Enamik uuritud kirikuid oli kaetud keraamiliste katusekividega, samas leidub ka puidust, valtsplekist ning tsementkiudplaatidest katuseid.

Vanimad on 20. sajandi keskel ning teisel poolel paigaldatud tsementkiudplaatidest, valtsplekist, betoonkividest ja keraamilistest kividest katused ning nende tööiga on sageli ammendumas või seda juba teinud.

Tsementkiudplaatidest katuste põhilised probleemid on pragude teke ning tuule- ja lumekoormuse tagajärjel plaatide purunemine piki pragusid. Seoses suure tahvli formaadiga, tähendab selle purunemine ka ca 0.5-1m^2 katusepinna katmata jäämist ning läbijooksu (Joonis 1.25 vasakul). Samuti on katuselt alla kukkuv materjal ohuks allviibijatele. Kui tsementkiudplaatkatuse all on säilinud teatava veepidavusega puitkatus, on otsesed kahjud väiksemad, kuid puudused tuleb sellegipoolest niipea kui võimalik ajutiste parandustöödega või uute tahvlitega kõrvaldada. Pikaajaline lahendus eluea lõpul olevatele katustele on muidugi katte täielik vahetus.

Plekki on peamiselt kasutatud tornikiivritel. Plekist katuste seisund erineb pea amortiseerunud katustest (Joonis 1.28) kuni täiesti uuteni. Kahjustunud või ammendunud tsinkkattega, kuid seni veel veetihedatel katustel, on võimalik eluiga pikendada kasutades spetsiaalset värvi. Värv peatab terase korrosiooni, mis kaitsekatteta areneb väga kiirelt. Seda meedet tuleks rakendada vastavalt hooldusvälbale kuni uue katusekatte paigalduseni.

Nõukogudeaegsed keraamilised katusekivid on tuntud oma kõikuva kvaliteedi poolest. Nende valmistamiseks kasutatud savis leidub paekiviosakesi. Kuna põletustemperatuur ja –aeg polnud väga hästi kontrollitud, muutus paekivi kõrgetel temperatuuridel põletades kustutamata lubjaks (CaO). Kui vesi lubjaosakeseni jõuab, paisub see hüdraatumisprotsessi käigus ning põhjustab pragude teket ning tugevuskadu.

Lisaks puudustele materjalide osas, tuleb välja tuua ka vajakajäämisi paigalduse ja ehitustehnoloogia osas. Kivid pole alati roovitusele traatsidemetega seotud (Joonis 1.28 paremal), mis põhjustab tugevate tuulte korral kivide eemaldumist oma kohalt või katuselt üldse.

Kivikatte ebatiheduse tõttu on võlvidele tuiskava vihma/lume ja kivide võimaliku purunemise/kao mõju vähendamiseks vajalik aluskate. Kuna tegemist on Eestis suhteliselt uue praktikaga, on üle 20 aasta vanustel katustel põhikatte alt aluskate valdavalt puudu. Aluskatteks sobib tihelaudisel olev kummibituumen rullkate. Esineb näiteid, kus aluskate on paigaldatud pärast ülejäänud katusekihtide valmimist katusetalade vahele – paraku pole selline lahendus väga töökindel (vt. Joonis 1.27 vasakul) ning aluskatte peale kogunenud vett on keeruline ära juhtida.

Vanemate kivikatuste puhul oli kasutusel S-kivi, siis uuemad katused on munk-nunn-tüüpi kividest. Katusekatte hermeetilisuse tagamiseks vajalik aluskate põhjustab seda, et katustel hooldustööde tegemine (kivide vahetus) vajab kõrgtööde spetsialistide ja/või eritehnika abi. Kuna kahjustuste kõrvaldamine võtab tõenäoliselt küllalt palju aega, on puuduva või kahjustatud aluskattega katused seetõttu kõrgema riskiastmega.

2000ndatel ja hilisemal perioodil rajatud katused olid heas seisus ning olid rajatud hästi väljatöötatud tänapäevase hea tavaga kooskõlas oleva katusetarindina (kivikate kummibituumen rullmaterjalist aluskattel). Kummibituumen aluskate arvestab oma tugevuse ja vastupidavusega hästi maakirikute omapäraga, sest on võimeline takistama vee jõudmist hoonesse ka juhul kui keraamilistest kividest katusekate on kahjustatud.

Vaatamata osalistele pingutustele probleemi lahendamiseks, olid mitmetes kirikutes siiski pööningul ja kirikutornis linnupesad. Lindude ekskrement on ebasanitaarne ning rikub konstruktsioone visuaalselt, kuid võib omada ka lagundavat mõju. Lisaks lindude minematõrjumisele ja pesade kõrvaldamisele tuleks vältida ka nende naasmist (vt. Joonis 1.29). Tuulutus- ja muud avad (ka räästas) tuleks lahendada nõnda, et linnud sealt läbi ei pääseks, nt. metallvõrguga kattes. Linnutõkked vajavad perioodilist kontrolli ja hooldust.

Joonis 1.24 Katusevõlvide peale tuisanud lumi, mis sulades valgub laevõlvidesse (vasakul). Aknast puitpõrandale tuisanud lumi (paremal).

Joonis 1.25 Vasakul: juba ühe tahvli purunemine on tsementkiudplaatkatustel tõsine probleem – korraga hakkab lekkima suhteliselt suur pind katust.
Paremal: oma kohalt nihkunud munk-nunn katusekive pole võimalik seest korrastada, katus võib jääda pikaks ajaks lekkima.

Joonis 1.26 Kivikatus vajab aluskatust – läbituiskav lumi ja vihm põhjustavad täiendava niiskuskoormuse, samuti on aluskate abiks kivide võimaliku purunemise/kao puhul.

Joonis 1.27 Hiljem lisatud aluskatte töökindlus on väiksem, samuti ei pruugi aluskate olla korrektselt väliskeskkonda viidud, vaid juhib sademed konstruktsioonidesse.

Joonis 1.28. Vasakul: valtsplekist katusekate.
Paremal: Kivikatus vajab aluskatet ja kivide kinnitamist katuseroovide külge.

Joonis 1.29 Lind on alustamas kirikuvõlvidele pesamaterjali tagasitoomist.

1.3.6.2 Kandekonstruktsioon

Katuste kandekonstruktsioonid on maakirikutes pea eranditult puitfermid, mis toetusid kandeseintele- ja postidele, kuid mõnel juhul ka võlvile.

Enne 20. sajandi keskpaika rajatud konstruktsioonid koosnevad käsitsi tahutud palkidest; põhilised liitedetailid on puitnaaglid, tihti on metalldetaile kasutatud ainult alumise vöö tõmbeliites (Joonis 1.30 vasakul). Kontakt niiskete konstruktsioonidega loob soodsad tingimused puidukahjustuste tekkeks. Kandevõime kontrollarvutusi uuringu käigus ei teostatud, kuid visuaalse vaatluse käigus oli vanemate katusekonstruktsioonide puhul pakiline hooldusvajadus nii liidete (vt. Joonis 1.30) kui materjali osas ilmne. Nõukogudeaegseid katusekonstruktsioone iseloomustab laialdane tööstuslike materjalide ja terasdetailide kasutamine. Peale 2000ndaid aastaid taastatud katustele on iseloomulik olemasoleva konstruktsiooni kasutamine ja defektsete detailide vajaduspõhine väljavahetamine ja plommimine (Joonis 1.32 paremal, Joonis 1.33). Samuti on laiendatud katuseräästaid, et pakkuda fassaadile mõnevõrra paremat kaitset vihmavee eest (Joonis 1.40).

Katusekonstruktsiooni seisund sõltub suurel määral katusekatte seisukorrast – kui konstruktsioonid on ilmastikutingimuste eest kaitstud (katusekate ja aluskate on terved), on puitosad heas korras ning valmis ka tulevikus korrektselt toimima. Kahjustatud konstruktsiooniosad olid harilikult kontaktis niiskete või märgade pindadega (sõrestiku toetus seinale, lekkekohad katuses, jne).

Ülevaatuse käigus avastati mitmel juhul vanematel puitdetailidel putukate lennuavasid. Kuigi need olid märgid varasemast kahjurirünnakust ja käesoleva uuringu käigus värskeid jälgi ei leitud, tuleb konstruktsioone sellegipoolest perioodiliselt kontrollida. Vanemad terasdetailid olid korrosiooni eest pinnakatetega kaitsmata ning ka vihma eest kaitstud osadel oli õhuniiskusest tingitud aeglane korrosioon märgatav.


Joonis 1.30. Vasakul: deformeerunud tõmbeliide põhjustab katusesõrestiku geomeetria muutust ning potentsiaalselt ka täiendava horisontaalkoormuse müüritisele.
Paremal: puitnaagliga liide on deformeerunud ja vajab kiiret sekkumist.


Joonis 1.31. Vasakul: lekete ja niiske müüritise tõttu märgunud puitkonstruktsioon on kasvukoht mädanikseentele. Paremal: hävinud katusesõrestiku liide vajab kiiret sekkumist.


Joonis 1.32. Vasakul: kuigi avastatud lennuavad olid vanad, tuleks puitkonstruktsioone perioodiliselt jälgida ning vajadusel abinõud tarvitusele võtta.
Paremal: viimastel aastakümnetel on terve katusekonstruktsiooni väljavahetamise asemel esialgset vajaduspõhiselt korrastatud.

Joonis 1.33 Eeskujulikult renoveeritud katuse kandekonstruktsioon. Varjatud kruvidega puiduliited.

1.3.7 Vihmaveesüsteemid ja räästad

Enamikul uuritud kirikutest oli väga kitsas räästas ning puudusid vihmaveesüsteemid – Joonis 1.34 esindab tüüpilist situatsiooni. Kahjuks polnud mitmel katuse restaureerimisel seda suurt probleemi likvideeritud. Tõenäoliselt kaalus kahjustuse põhjuseks olev ajalooline lahendus restaureerimislahenduse väljatöötamisel üles kahjustuse põhjuse vähendamise või likvideerimise. Halvimal juhul polnuid kahjustuse põhjustuse likvideerimisele restaureerimisel mõeldudki.

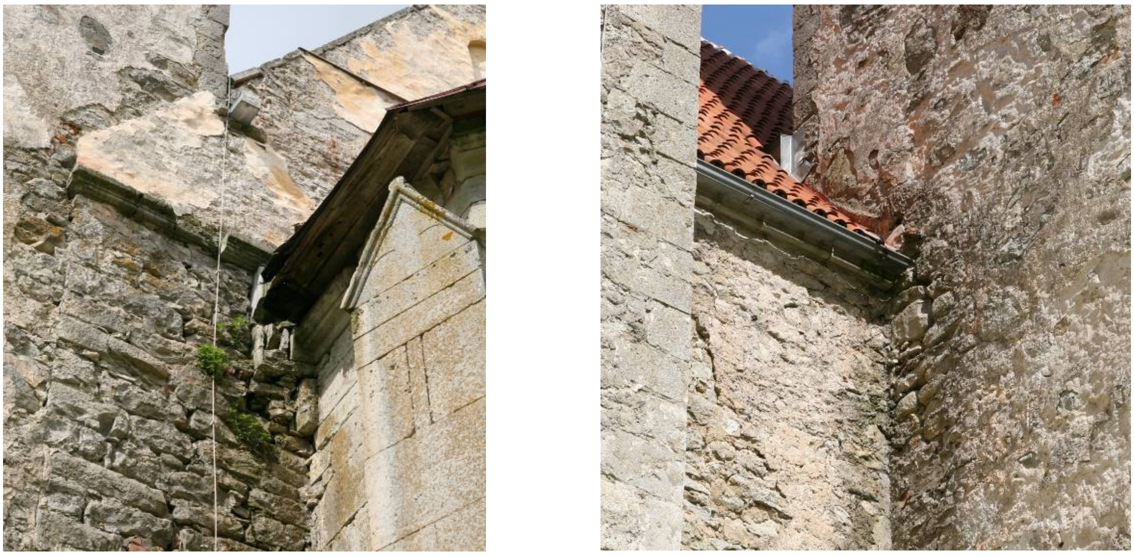
Kaldvihm ja ebatasasused fassaadiosal mida räästas ei kata põhjustavad suurt veekoormust. Fassaadi märgumisel on mõju nii esteetilisest kui konstruktsioonilisest küljest. Külmumis-sulamistsüklite mõjul laguneb krohv, pragunenud ja pudenenud krohvi tõttu märgub ka selle taga olev müüritis. See omakorda kahjustab müüritise kandevõimet ja on teguriks seinte sisepinnal (vt. jaotis 1.3.3.3) probleemide tekkel. Viimast kinnitas ka mikrolainemeetodil seinte niiskussisalduse määramine ja tulemuste analüüs (vt. peatükk 7). Skemaatilise protsessi kirjelduse annab Joonis 1.1, hoone kõrguse kohta ebaproportsionaalselt kitsa räästa poolt kaitstud ala on nähtav fotol Joonis 1.34 (paremal).

Fassaadi hooldusvälba pikendamisele aitaks oluliselt kaasa räästa pikendamine ja rennide paigaldamine. On selge, et selliste hoone ilmet muutvate meetmete rakendamine ning sobivate lahenduste leidmine tuleb hoolikalt läbi mõelda, kuid nende positiivset mõju (krohvi, värvi ja müüritise pikem eluiga, madalam veevoog konstruktsiooni jne) ei tohiks alahinnata.

Kohtades, kus esineb kontsentreeritud koguseid sademevett (nt. neelud, läbiviigud seintest/parapettidest, pikad katusekalded jne), on korrektsed vihmaveesüsteemid hädavajalikud, et vett hoonele ohutult ära juhtida (vt. Joonis 1.37 kuni Joonis 1.35).

Näiteid renoveeritud vihmaveesüsteemi osadest annavad Joonis 1.39 kuni Joonis 1.42. Muhu kiriku näitel (vt. peatükk 7.6.1) toimivad seinte veekoormuse vähendamisel hästi ka laiendamata räästaga vihmaveerennid ja –torud. Probleeme sealsete rennide puhastamisega ei ilmnenud, samuti oli torudest maapinnale jõudnud vihmavesi hoonest eemale juhitud.

Joonis 1.34 Kitsas rennide ja vihmaveetorudeta räästas ei kaitse fassaadi vihma eest ning on teguriks nii fassaadi määrdumisel ja lagunemisel, aga ka kahjustuste tekkel seinte sisepinnale.



Joonis 1.35 Korrektsete vihmaveesüsteemide varasem puudumine on põhjustanud fassaadi tõsist kahjustumist.

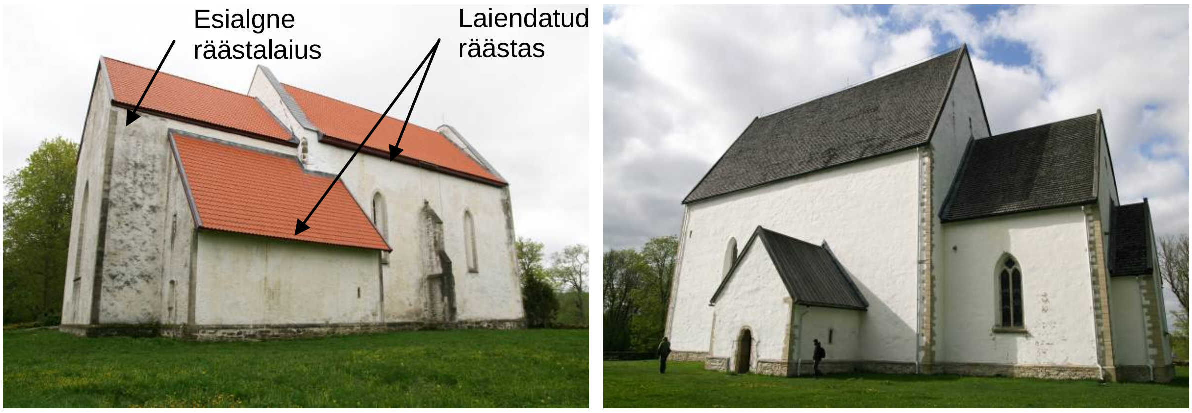
Joonis 1.36 Vasakul: töö on jäänud poolikuks: vihmaveetorust valgub vesi seinale.
Paremal: katuse küljeplekk ulatub üle renni, fassaadil on külmakahjustused.

Joonis 1.37 Katuserääastad on liiga lühikesed ja ilma vihmaveerennideta. Katuselt allalangev vesi kahjustab välisseinu: mört on kivide vahelt välja uhutud, samuti on nähtavad külmakahjustused.

Joonis 1.38 Katuselt valgub vihmavesi otse välisseinale. Tulemuseks on kahjustunud välisseinad ja seinamaalingud.

Joonis 1.39 Puhas vihmaveerenn (vasakul) ja hoonest eemale juhitud vihmavesi (paremal).

Joonis 1.40 Laiendatud räästas. Puudu on veel vihmavee äravoolusüsteem.



Joonis 1.41 Vasakul: Karja kirik osaliselt esialgse ja osaliselt laiendatud räästaga, puuduvad vihmaveerennid ja –torud. Kitsa räästaga seinaosal on suurem veekoormus ilmne. Paremal: Muhu kirik esialgse räästalaiuse ja vihmaveerennide ning -torudega.

Joonis 1.42 Käärkambri katuselt on vihmavee äravool korraldatud korralikult. Katusepleki ülepööre seinale on jäänud 15…20cm liiga madalaks (vasakul). Otsaseina juures on katuse üleulatus seinast lubamatult väike (paremal).

1.3.8 Põrandad

Põhiliselt oli uuritud kirikutel kiviplaatidest põrandad, aga esines ka puitpõrandaid ning kivipõrandale rajatud puitpõrandaid.

Seoses hüdroisolatsiooni ja drenaaži puudumisega on põrandate all nii pinnase niiskussisaldus kui õhu veeaurusisaldus kõrge. Sellised tingimused on soodsad hallitus- ja mädanikseente kasvuks ning erinevate ehitusvigade (seisev õhk, otsekontakt märgade pindadega jms) tõttu oli üks uuritud puitpõrandad nakatunud hallitus- ja mädanikseentega. Mädanikseened võivad sobivates tingimustes kiirelt edasi levida ning hävitada terve põranda. Paari viljakehaga põrandal (Joonis 1.43) võib välisel vaatlusel üldiselt olla kõik korras, aga konstruktsiooni avamisel selgub olukorra tõsidus. Avastatud kahjustustel tuleb nende täielik ulatus kiirelt kindlaks teha ning seente täiendava leviku vältimiseks (nii seeneniidistiku kui eoste kaudu õhus) need viivitamatult kõrvaldada. Nakkuse kordumise vältimiseks tuleb täpselt täita spetsialistide ettekirjutusi ning ühtlasi likvideerida probleemi tekkepõhjused. Lisaks põhjalikule tööle on vajalik ka järelkontroll.

Kivipõrandatel põhiline puudus oli vähemal või enamal määral (Joonis 1.44 paremal) esinenud ebatasasus, mis raskematel juhtudel külastajate kukkumisi ja seeläbi vigastusi põhjustada võib. Pinkide ja muude puitdetailide paigutamisel kivipõrandale polnud alati arvestatud paeplaatide kapillaarse veejuhtivusega ning puidu kahjustusi esines nendelgi.

Joonis 1.43 Mädanikseenega kahjustatud puitpõrand pealt (vasakul) ja alt (paremal).

Joonis 1.44 Vasakul: seenkahjustustega puitpõrand.
Paremal: suurte ebatasasustega paeplaatidest põrand.

1.3.9 Tuleohutus

Kirikute tuleohutust silmas pidades ilmnes puudusi elektrisüsteemidega ning tulekahjuanduritega.

Tüüpiline oli, et elektritööd pole teostatud terviklikult (s.t. osaliselt olid kasutusel nõukogudeaegsed paigaldised), seejuures oli tööde kvaliteet tihtipeale kõikuv ning dokumentatsioon puudulik (nt. Joonis 1.45).

Kõigile kirikutele oli paigaldatud piksekaitse, selle kui süsteemi toimivust uuringu käigus ei hinnatud. Visuaalsel vaatlusel tuvastati probleeme piksekaitse kinnititega – esines juhuseid, kus kasutatud ~4x40mm tüüblid ei moodustanud lubikrohviga piisavalt tugevat liidet ning olid seinast lahti tulnud. Korralikult kinnitamata süsteem võib tuule mõjul puruneda, põhjustada naaberkonstruktsioonidele täiendavaid kahjustusi ning ühtlasi pole hoone enam kaitstud.

Tulekahjuandureid polnud kõikidesse kirikutesse paigaldatud. Tähelepanuväärne oli ka, et paigaldatud andurite töökord ja ühendus päästeameti/turvateenistusega polnud alati tagatud.

Joonis 1.45 Kirikute elektripaigaldised on sageli puuduliku dokumentatsiooniga ja tänapäevastele nõuetele mittevastavalt teostatud.

1.4 Kokkuvõte

Kirikute ehitustehnilise seisundi ülevaade tõi jälle välja kirikute probleemse olukorra. Maakirikute kogudustele, kui mälestiste omanikele, on muinsuskaitseseadusega pandud kirikute, kui mälestiste, remontimise, säilitamise ja korrashoiu nõudega, saavutamatud kohustused. Saavutamatute kohustuste seadmisega on oht kohustuste olulisuse hajumisele ja vastutustundetuse tekkimisele.

Koguduste kui kirikute majandusüksuste majanduslik olukord võimaldab tegeleda tihtipeale vaid hingehoiuga, parimal juhul ka hoonete hädapärase hooldusega. Suuremad ehitus- ja hooldustööd vajavad täiendavat välist rahastust. Kirikute sisekliima tagamine mäletse ja selle sisustuse säilimiseks on aastaringne tegevus. Kui maakirikut kasutatakse hingehoiuks vaid nädalavahetustel, vajab ka sisekliima tagamise eest tasumine välist tuge.

Jätkusuutlikuks haldamiseks on tarvilik vältida olukorda, kus väärtuslikud ressursid kulutatakse ebaotstarbekalt: kahjustuste tagajärgedega võitlemisele ilma kahjustuste põhjuseid likvideerimata. Kirikute olemasolev ehitustehniline olukord ja vajalike tööde prioriteet tuleb enne hooldus- ja taastamistöid hoolikalt välja selgitada. Paljude probleemide juures tuli ilmekalt välja, et probleemide tagajärgede likvideerimisega oli tegeletud kuid probleemi tekkepõhjus oli ikkagi jäetud likvideerimata. Restaureerimisel, konserveerimisel ja renoveerimisel tuleb esmalt kõrvaldada kahjustuste põhjused ning seejärel tegelda defektsete osade restaureerimisega ja konserveerimisega. Konserveerimise ja restaureerimise ehitusprojektid olid üldiselt napisõnalised konserveerimise ja restaureerimise lahenduste kestvuse ja eluea osas, samuti piirdetarindite ehitusfüüsikaline käsitluse, sisekliima nõuete ja selle tagamise mooduste osas (Kultuuriministri määruse nr 15 „Kinnismälestiste ja muinsuskaitsealal paiknevate ehitiste konserveerimise, restaureerimise ja ehitamise projektide koostamise ning neis eelnevate uuringute tegemise tingimused ja kord“ nõuded).

Kirikute ehitustehnilise seisundi jälgimisega tuleb järjepidevalt ja süstemaatiliselt tegeleda, et võimalikke probleeme avastada faasis, kus kahjustused pole liiga kaugele arenenud ja nende likvideerimine on juba palju ressursimahukam. Järjepidev hooldus ja kiire reageerimine võimalikele puuduste likvideerimisel tagab suuremate kahjude vältimise. Kuna mälestiste puhul on tähtis nende säilimine ka tulevaste põlvede jaoks, siis pikas perspektiivis on jätkusuutlik eelkõige probleemide ennetamine ja tekkepõhjuse kõrvaldamine, mitte korduv tagajärgede likvideerimine.

Senisest oluliselt rohkem ressursse tuleb panustada ka restaureerimise, konserveerimise ja renoveerimise lahenduste väljatöötamiseks ning kestvuse ja töökindluse testimiseks. Tuleb arvestada, et mitmed kirikutes kasutatavad ajaloolised materjalid võivad olla madalama vastupidavusega kui mõned tänapäevased analoogid. Seeläbi vajavad nad kas tihedamat hooldusvälpa või hoolikamat suhtumist lagundavate tegurite mõju vähendamisse.

Joonis 1.46 Kirikute jätkuva hooldusega, konserveerimisega, restaureerimisega tuleb tagada olukord, et kirik poleks ”*Danger area*”.

1.5 Tänusõnad

Autorid tänavad Simo Ilometsa, Endrik Arumäge, Jaanika Saart, Üllar Alevit, Andres Uut, Eero Tuhkaneni, Lembit Kurikut and Urve Kallavust Tallinna Tehnikaülikoolist abi eest kirikute tehnilise olukorra väljaselgitamisel ning Juhan Kilumetsa ja Eva Mölderit OÜ-st Rändmeister kirikute restaureerimise ja hooldamise ajaloo kirjeldamisel.

2 INDOOR CLIMATE IN A NATURALLY VENTILATED UNHEATED MEDIEVAL CHURCHES

Targo Kalamees, Alan Väli Lembit Kurik

2.1 Introduction

The indoor climate in unheated churches is mainly influenced by the outdoor climate. Hence, over the centuries, a stable indoor climate develops with slow changes in temperature and humidity. Medieval churches are built with massive stone walls whose thermal and hygroscopic mass helps stabilise the variations in temperature and humidity. Their large thermal mass keeps the church cooler in spring and warmer in autumn. Low surface temperature causes the rise of relative humidity. The thermal resistance of windows and external walls is low; as a result, the temperature of the building envelope can be low and surface RH high.

Establishing suitable indoor climate for old churches is a complex task. The conservation of culturally valuable structures and details must be considered and if possible, a suitable indoor climate created for visitors. For people, the most important indicator of thermal comfort is temperature; from the perspective of conservation of cultural treasures, however, the most important physical indicator is relative humidity. Hence, an indoor climate suitable for the church's interior and structural parts might not be suitable for people. Making the indoor climate of churches more comfortable for people requires increasing the indoor temperature. Changing the indoor temperature, however, also alters relative humidity. Changes in relative humidity might damage the interior of the church: cracks in wooden details and the organ, stains on walls, flaking plaster and damaged murals. One solution for excessive dryness can be humidification; however, in this case, relative humidity can only be increased to a certain extent in order to avoid condensation on surfaces which in turn can cause damage like rot and mould fungi, algae, etc.

A number of studies have been carried out in the past with goal of studying the climate in heated or periodically heated churches but data on unheated churches is far less comprehensive. The indoor climate of naturally ventilated unheated medieval churches was analysed in order to determine climatic risks to organs, valuable pieces of art and details of high cultural value. Major risks include unsuitable relative humidity and temperature. Too high RH in combination with high enough temperatures can cause mould to grow, wooden parts to decay and surfaces to become soiled. Fluctuations in temperature and RH can cause cracks in paintings and wooden sculptures. Too much humidity in combination with a low surface temperature can cause water vapour to condensate on the cooler surfaces of the building envelope.

In this study, an overview of the current indoor conditions and suggestions for changes are presented. The risk assessment for indoor objects is based on literature and measurement results from churches.

2.1.1 Indoor climate requirements for churches

Establishing a suitable indoor climate in old churches is a complex task. It is important to ensure that objects of cultural value are preserved in conditions which will harm neither their properties nor value. Different studies have established several criteria for the indoor climate of churches. A summary of the results is presented in Table 2.1.

The lower temperature limit is determined by the comfort of visitors and the requirement to prevent temperature from dropping below zero. The upper limit is determined by relative humidity. Based on different studies, suitable indoor temperature falls between +8…+10 °C, maximum +15 °C for the service (in colder periods, maximum +12 °C). The most suitable temperature range for the organ is between +10…+20 °C. Temperatures between +7…32 °C are the best for pianos.

Another factor to consider besides the overall temperature is the rate of temperature fluctuations. Sudden fluctuations can damage the interior of the church. Rapid changes in temperature may create differences in a material's surface temperature and temperature inside the material. Fast temperature changes can also cause differences in the interior temperature of different part of the church. This may cause temperature fluctuations in the same object. Materials have different heat- and moisture capacity; as a result, they heat up and cool, moisten and dry at a different rate. This can cause excessive volumetric changes and internal tensions in materials when the temperature change is too fast. No lower limit has been established for the rate of temperature change. The optimal rate of temperature change in churches has been established to be 1…2 degrees per hour (Schellen 2002).

The lower limit for relative humidity is mostly established to prevent the excessive drying of the organ and wooden parts and salt crystallization on surfaces. The upper limit is determined by the growth of the mould and abscess and condensation on walls and on windows.

The organ is not affected by ambient temperature. It is, however, affected more by relative humidity. Hence, relative humidity inside the church is mainly defined by the organ's requirements. Several authors have offered different optimal relative humidity for organs: Stadtmüller 1972: 60-70%, Supper 1967: 60%, Schlieder 1967 & 1969: 50-80%, Badertscher 1965: 45-65%, IBO 2003: 55%...75%.

Deviations in relative humidity cause salt to crystallize in stone materials. Salt crystallization also causes expansion that can damage plaster and stone materials. Fluctuations in humidity near the level required for crystallization can be particularly dangerous.

For mould to grow, relative humidity needs to be greater than 70…80%. The lower the temperature, the higher the relative humidity needs to be for mould growth.

Table 2.1 Recommended indoor climate parameters

	Indoor temp. $t_{primary}$, °C	Outdoor temp. $t_{service}$, °C	Relative humidity, RH, %	Relative humidity amplitude, $\Delta RH_{öp}$, %	Temp. fluctuation rate, $\Delta t/\Delta h$, K/h	Air velocity, u, m/s	Floor temperature, t_{floor}, °C
Schellen, 2002	<8…10	<12…19	>45…50, <60…75	10 (day), 30 (year)	<1…2	0.1…0.3	25…28
Schlieder 1969, 1967	7…10	≤15	50…80		<2		<25
Mayer, 1981		7…10	40…60			<0.1	
Gossens, 1977	8…10	12...15	50…60		1.5…2		
Stadtmüller, 1972			60…70				
Badertscher, 1965	6…8	≤15	45…60				
Supper, 1967	5…7	17…19	<60				
Bordass, 1983/1996	≤10		45…65		<1.5	<0.15	
DIN 1946						0.1…0.3	
Arendt, 1976, 1981, 1993, 1995	≤9	≤12					
Schmidt-Thomson, 1972	8	12…15			<1.5		
Knol, 1971		≤15	<75		<1.5		
Mainz, 1972		12…15			<1.5		<25
Vorenkamp, 1993	8	<18			<1		
Künzel, 1991	5…8	12…16	50…80	10 (day), 30 (year)			
Hennings, 1966	8	15	55…75			<0.15	<15

Suitable relative humidity inside churches is presented in Figure 2.1.

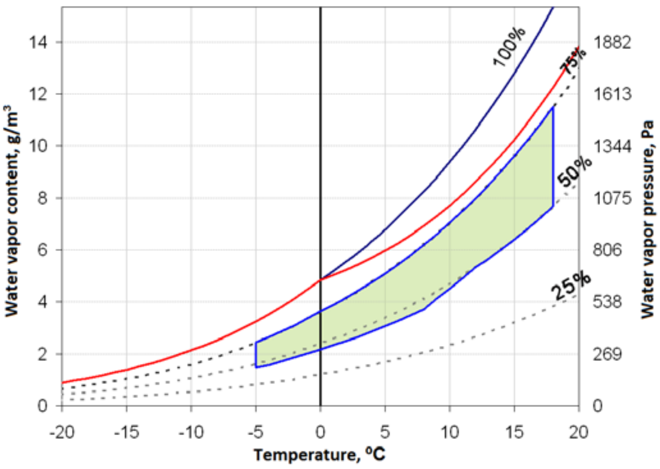


Figure 2.1 Suitable indoor relative humidity (green area).

2.1.2 Purpose of the study

Data about indoor climate in churches is necessary:

- for an overview of the current situation of medieval churches;
- for background information required for the conservation, restoration and preservation of interior objects, art treasures and organs;
- for a comparison of heated (Gotland) and unheated (Saaremaa) churches (with a largely similar outdoor climate);
- to find building properties to characterise of indoor climate in medieval churches;
- to correlate damage found in churches with indoor climate parameters;
- to confirm or refute the connection between damage and indoor climate.

2.2 Methods

2.2.1 Studied churches

The objects of this study were ten unheated medieval churches located in the Western part of Estonia. Seven of them were situated in Saaremaa and three of them in the mainland. Exact locations are shown in Figure 2.2. The churches were all of different size and with different characteristics (Table 2.2). Their most valuable parts were the organs, altars, chancels, art treasures, but also sculptures and wall paintings. The technical conditions of the churches were different. The main technical factors influencing indoor climate were large cracks around doors and broken or cracking windows. On the walls, the growth of algae and salt crystallization could be observed. Whereas the growth of algae is mostly an aesthetic problem on stone walls, crystallization has caused cracks and flaking in the plaster.

Figure 2.2 Locations of studied unheated medieval churches in Estonia

Table 2.2 Studied Estonian churches (Lutheran)

Church	Net area, m^2
1) St Peter`s and St Paul`s Church in Kaarma	484
2) St Catherine`s Church in Karja	358
3) St Michael`s Church in Kihelkonna	426
4) St Catherine`s Church in Muhu	292
5) St Martin`s Church in Valjala	344
6) St James` Church in Püha	267
7) St Mary`s Church in Pöide	514
8) St Margaret`s Church in Karuse	265
9) Church of the Holy Cross in Risti	300
10) St Mary Magdalene`s Church in Ridala	406

As the churches were not far from each other, the outdoor climate was relatively similar in all cases. This made the measurement results more comparable.

2.2.2 Measurements

Indoor temperature and humidity

Data was collected over a 12 month period in 2012 and 2013. Temperature and RH were measured with Hobo U – 12 011 data loggers (Table 2.3) at one hour intervals inside the churches. Outside values were also measured in some cases using the Hobo U-12 011; for some churches, the data is based on Estonian Environment Agency`s measurements near the studied churches.

Table 2.3 Specifications of the measuring device for temperature and relative humidity

Hobo U-12 011	Measurement range:	
	Temperature:	Relative Humidity:
	-20 °C…+70 °C	5%...95%
	Measurement accuracy:	
	Temperature:	Relative Humidity:
	±0,35 °C	±2,5%
	In the range 0 °C…50 °C	In the range 10%…90%

Indoor data loggers were placed in three locations (Figure 2.3):

- Behind the altar, about 1.6 meters from the floor
- Centre of the church hall under a bench, about 0.4 meters from the floor
- Inside the organ, about 5 meters from the first floor (where possible; see Figure 2.3).

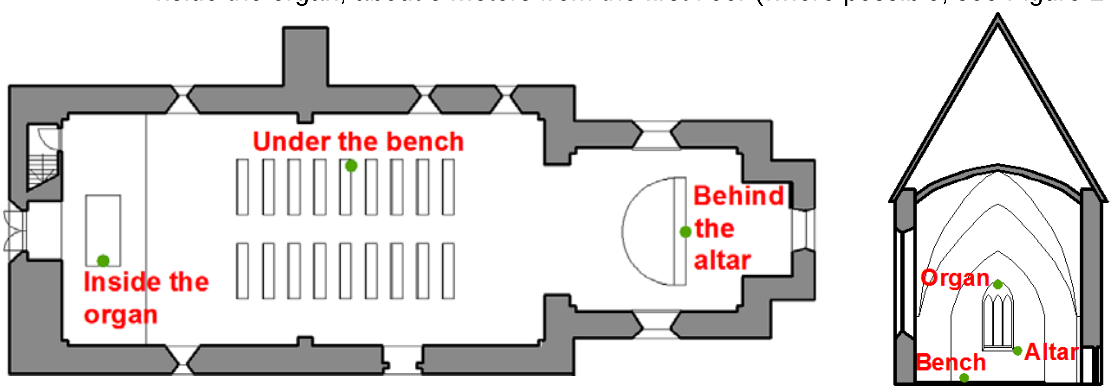


Figure 2.3 Locations of temperature and RH loggers in churches; top (left) and section (right)

A B C

Figure 2.4 Locations of data loggers are marked with red circles: A: Under the bench
B: Inside the organ
C: Behind the altar

Conditions on Facade/Envelope

The temperature of the building envelope was measured in the following churches:

- St Martin`s Lutheran Church in Valjala
- St James` Lutheran Church in Püha
- St Catherine`s Lutheran Church in Karja

The purpose of measuring surface temperatures was to study the differences in temperature fluctuations on the surface of the building envelope and in the surrounding indoor environment.

Surface temperatures were measured with thermistor sensors and the results were saved using Hobo data loggers (Figure 2.5)

A B C

Figure 2.5 A: Principle of envelope condition measurements
B, C: Sensors in the church, marked with red circles

Spatial Distribution of Temperature and Relative Humidity

Air temperature and RH were mapped on a 5×5m grid for an overview of temperature and RH distribution. Spatial distribution was studied in the following churches:

- St Catherine`s Lutheran Church in Muhu
- Lutheran Church of the Holy Cross in Risti
- St Peter`s and St Paul`s Church in Kaarma
- St Martin`s Church in Valjala

Measurements were made about 0.4 meters above the floor using Hobo U-12 011 loggers (Figure 2.6). The measurement devices were set to log relative humidity and temperature with a minimum interval of 30 seconds for a period of two minutes at each measurement point. Isolines for temperature and RH were plotted on the basis of the measurement results.

Figure 2.6 Sensors for measuring the spatial distribution of temperature and relative humidity, marked with red circles

2.2.3 Assessment of Indoor Climate

Requirements for internal conditions are based on several factors. The lower temperature limit is usually based on overall thermal comfort and the upper limit is related to relative humidity. It means that an indoor climate suitable for the structure and indoor objects can be uncomfortable for visitors. In this study, current conditions of thermal comfort were not assessed as the churches were all unheated.

The lower limit of relative humidity is established with the goal of preventing the excessive drying of indoor wooden parts and the organ, and the risk of salt crystallization on the building envelope. The upper limit is related to the risk of mould growth.

Since temperature, relative humidity and moisture content were stable and without large variations in the churches, average measurement results from all data loggers placed in a church were used for calculations.

Mould growth

The assessment of the risk of mould growth was based on experiments (Viitanen, 1997; Lähtesmäki et al 2008) establishing the limit curve for the risk of mould growth on wooden materials in the temperature range of 5–40 °C. This limit curve can be described using the polynomial function:

$$RH_{crit} = \begin{cases} -0.0267 \cdot t^2 + 0.160 \cdot t^2 - 3.13 \cdot t + 100 & ,when \quad t \leq 20^{\circ}C \\ 80\% & ,when \quad t > 20^{\circ}C \end{cases} \qquad \text{Equation 1}$$

The risk of mould growth was assessed by applying an existing standard index based on the visual appearance of the surface to the studied test samples. The mathematical model for mould growth developed in Finland (Viitanen, 1997) includes a mould growth index determined by mould growth rate:

- 0: no growth, spores not activated;
- 1: some growth detectable only with microscopy, initial stages of hyphae growth;
- 2: moderate growth detected with microscopy (<10% surface mould coverage);
- 3: some visually detectable growth (10–30% surface mould coverage); new spores produced;
- 4: clear visually detectable growth (30–70% surface mould coverage), moderate growth;
- 5: plenty of visually detectable growth (>70% surface mould coverage);
- 6: very heavy and tight growth (nearly 100% surface mould coverage).

Mould growth risk assessment is based on the probability of an effect to occur. In the studied medieval unheated churches, the risk of mould growth is expressed as the percentage of the yearly cycle when relative humidity and temperature, measured at a one hour interval, exceed the critical curve of mould risk.

Wood fracturing

When assessing overall temperature conditions, it is also important to study the characteristics of the fluctuations. Too strong and fast fluctuations in temperature cause strong variations in the changes in relative humidity which lead to high internal tension in objects. When the temperature difference between the surface and inside of the material is too high, damage will occur. However, it must be understood that short fluctuations with high amplitudes will not influence objects as the response time of the material is longer than the duration of the fluctuation.

The cracking risk of wooden objects was studied. Materials have different heat and moisture capacities, meaning that they moisten and dry at different rates. When analysing the mechanical damage risk of indoor objects, the response value of indoor relative humidity was used. RH response at the moment i can be calculated using the following equation (Martens 2012):

$$RH_{response,i} = -\frac{RH_{response,i-1} + \frac{RH_i}{n/3}}{1 + \frac{1}{n/3}} \qquad \text{Equation 2}$$

$RH_{response}$	Object's response in RH [%]
RH	Relative Humidity [%]
i	Current data point in the data range [-]
n	Number of data points in response time [-].

The RH response value depends on response time which is different for different objects. For wooden sculptures, it is 10 hours, while RH response of the surface of panel paintings just under oil paint is 4.3 days (ASHRAE 2011)

The assessment of irreversible and reversible response is based on the Jakieła et al (2008) model. The model (Figure 2.7) was developed for a lime wood cylinder with a diameter of 13 cm that was in equilibrium with different RH levels. Diurnal changes were applied to cylinder and stresses leading to damage were calculated.

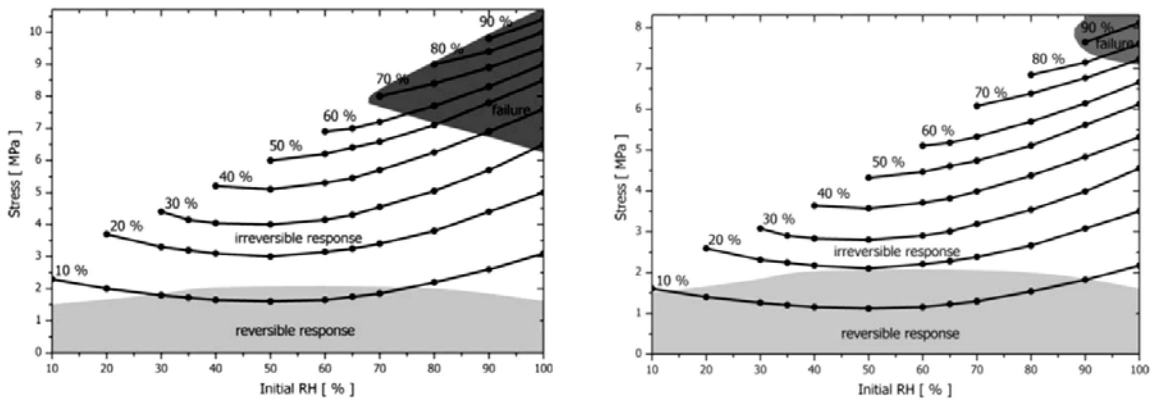


Figure 2.7 Stress response in relation to initial RH and plotted for different magnitudes of RH change and with the range for reversible response and failure displayed, for instantaneous RH changes. The white area between the two zones is where the response is between the yielding and failing points, *ergo* the area of irreversible deformation (Jakieła, Bratasz and Kozłowski, 2008). The same stress response in relation to initial RH as on the left but with the RH changes taking place over a 24 hour period.

In the present study, levels causing irreversible response in wooden objects dependent on initial RH were calculated on the basis of Figure 2.7 and the percentage of RH measurement results causing irreversible response in wooden objects was determined.

The assessment of the cracking risk of the gesso layer of panel paintings was carried out on the basis of Kozłowski's model [2011]. The model (Figure 2.8) shows permitted amplitudes of the sinusoidal RH cycles as a function of the cycle duration for an unrestrained panel of 10 mm thickness and a moisture exchange through one face at 5 and 20 °C.

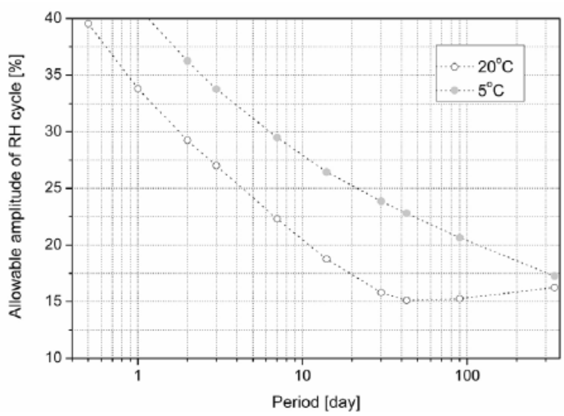


Figure 2.8 Allowable RH amplitudes for the gesso layer

In this study, the risk of cracking of the gesso layer was evaluated on the basis of 1, 7, and 30 day cycle amplitudes. Measurement results measured below 5 °C were evaluated on the basis of the risk curve for 5 °C; measurement results measured above 20 °C were evaluated on the basis of the risk curve for 20 °C. Risk values for measurement results between 5 and 20 °C were found on the basis of linear function between the values on the 5 and 20 °C curves.

As this model was worked out in conditions of 50% RH and for gesso layers without any cracks, it must be understood that using this method carries some risk of uncertainty.

2.3 Results

2.3.1 Outdoor Climate

Outdoor temperature and relative humidity were measured at a one hour interval. Data were obtained from the Estonian Environment Agency and measured with data loggers placed near the studied churches. The average monthly temperatures and RH in Saaremaa and the mainland are shown in Table 2.4 and overall outdoor climate during the measurement period is shown in Figure 2.9.

Table 2.4 Monthly average outdoor temperatures (t, ºC) and relative humidity (RH; %) in 2012 – 2013

	2012 - 2013											
	June T RH	July T RH	Aug. T RH	Sept. T RH	Oct. T RH	Nov. T RH	Dec. T RH	Jan. T RH	Feb. T RH	Mar. T RH	Apr. T RH	May T RH
Saaremaa	12.9 78	17.8 79	16.6 79	13.7 83	8.4 85	5.2 87	-3.2 90	-3.1 88	-1.7 90	-4.0 72	3.2 80	13.0 75
Mainland	12.6 76	17.7 77	16.2 75	12.9 83	6.6 88	3.4 88	-6.3 86	-4.2 88	-2.0 88	-5.9 70	3.5 73	12.2 67

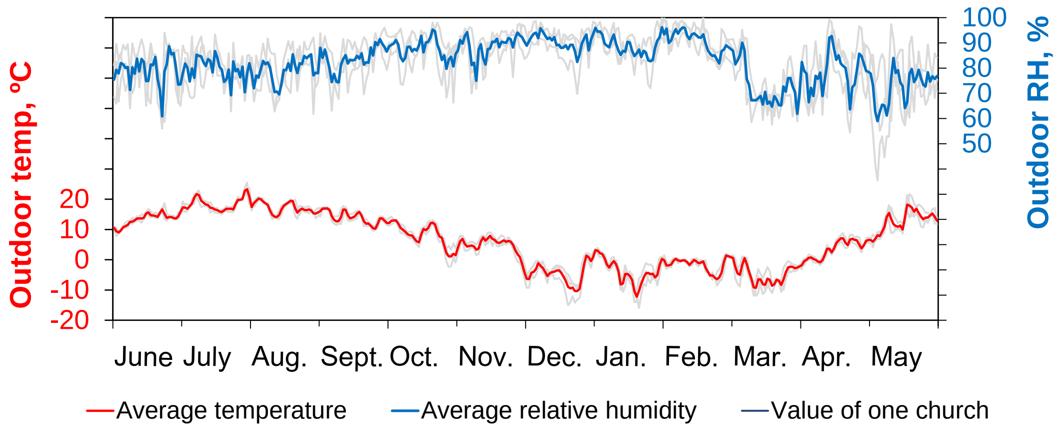


Figure 2.9 Average outdoor temperature and relative humidity during the measurement period

2.3.2 Indoor Climate

Temperature

As all the studied Estonian churches were unheated, indoor climate is directly related to outdoor conditions. The dependency between indoor and outdoor temperatures and average values for a one year period in one studied unheated church is shown in Figure 2.10. Measurement results are marked with green and average results are indicated by the red line.

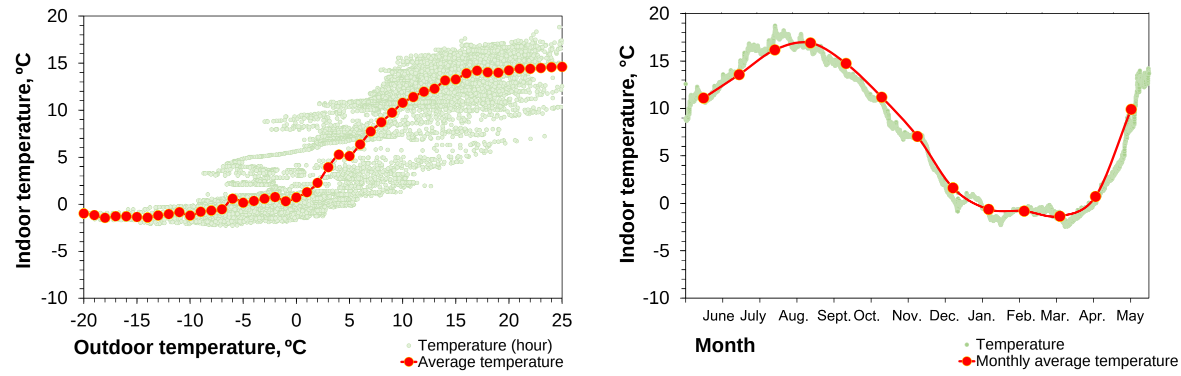


Figure 2.10 Dependency of a church's indoor temperature on outdoor temperature (left) and indoor temperature conditions during the measurement period (right)

The dependencies between indoor and outdoor temperature of all the studied churches are shown on the left in Figure 2.11. The average temperature of all unheated medieval churches during a one year period was +6.9 ºC. The highest yearly average temperature was measured in Kihelkonna Church, +7.6 ºC and lowest yearly average in Karuse Church, +6.3 ºC. On the right in Figure 2.11 are shown temperature values of different months. Average indoor temperature of all churches in summer was +15.4 ºC and in winter, -1.0 ºC. The highest summer average temperature was +16.1 ºC in Pöide Church and the lowest summer average was +14.5 ºC in Ridala Church. The highest winter average, +0.3 ºC, was measured in Kihelkonna Church and the lowest winter average, -2.2 ºC, in Karuse Church. Differences between the studied churches are very small.

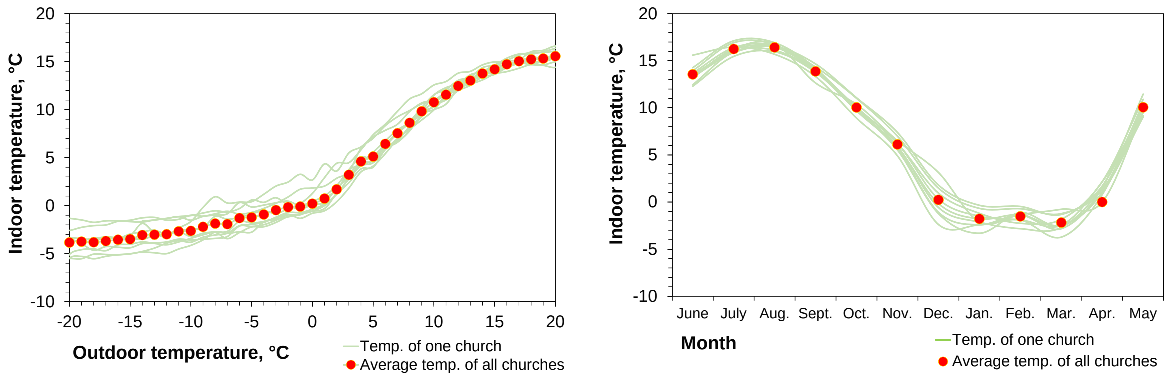


Figure 2.11 Dependency of indoor temperature on outdoor temperature in all churches (left) and indoor temperature conditions during the measurement period in all churches (right)

The temperature cycle of a one year period based on monthly average values is presented in Figure 2.12. It is important to note that when outdoor temperature is below 0 °C, then indoor temperature is also mostly below 0 °C. On the other hand, when outdoor temperature drops down to -20 ºC, average indoor temperature remains higher than -6 ºC. This is because the very low temperatures do not last very long and because due to the large thermal mass of walls, the indoor temperature does not respond as fast to the external temperature changes. The difference in temperature between the coldest and warmest month is about 20 °C..

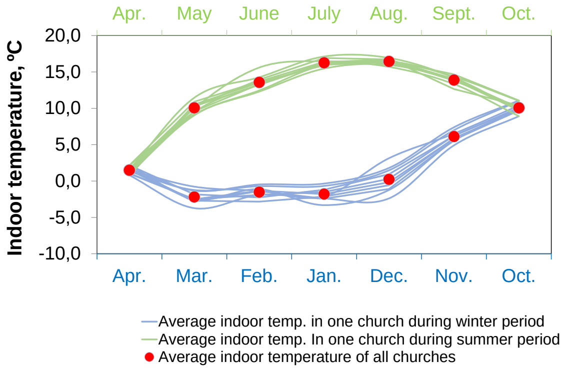


Figure 2.12 Temperature cycle in unheated churches based on monthly average values

The differences between indoor air, outdoor air and building envelope temperatures based on hourly measurements are shown in Figure 2.13. The Kaarma and Karja Churches are chosen to represent the temperature differences during the measurement period. As the churches are quite close to each other, outdoor climate data is based on measurements made near Kaarma.

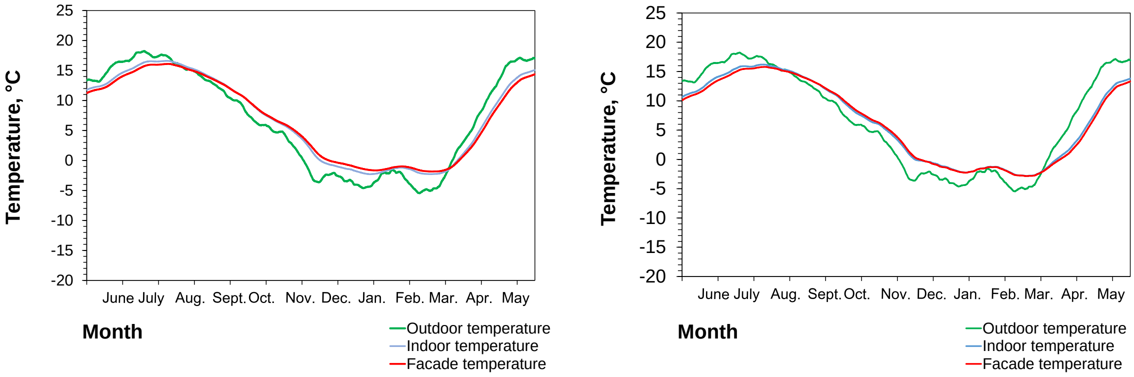


Figure 2.13 Temperature differences in Karja Church (left) and Kaarma Church (right).

Figure 2.13 shows the capacity of large thermal mass to stabilize temperature fluctuations. The average difference between surface and indoor temperature is 0.5 °C. It can be noted that in spring and summer, surface and indoor temperatures are mostly colder than outdoor temperatures while in autumn and winter, indoor air and surface temperatures are generally warmer than outdoor temperatures. The results show that indoor temperatures are relatively slow to respond to outdoor temperatures, depending on the condition of the church and the duration of the temperature fluctuations.

Relative Humidity

Relative humidity depends on the location, condition and usage of the church. Figure 2.14 shows the dependency between indoor RH and outdoor temperature and average values during a one year period in one studied unheated church. It can be noted that RH is very high during the year with maximum values up to 100%. Measurement results are marked with green and average results are indicated by the red line.

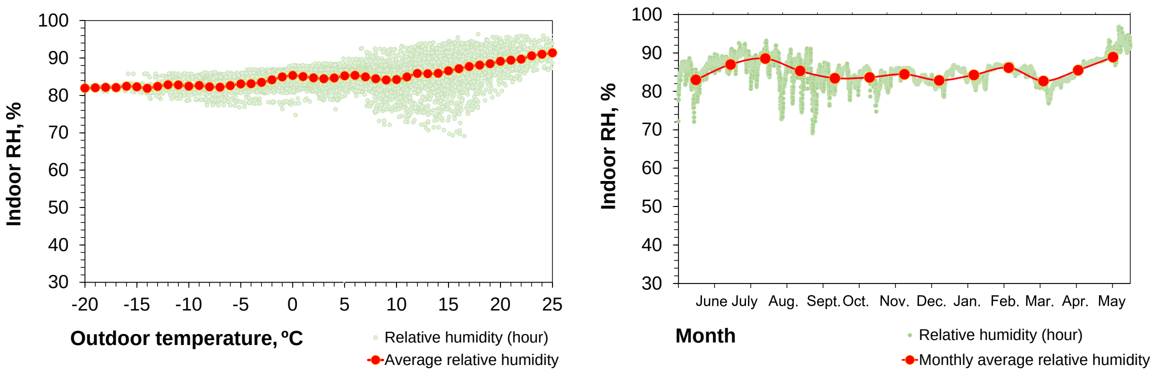


Figure 2.14 Dependency of indoor RH on outdoor temperature in all churches (left) and indoor RH conditions during the measurement period in all churches (right)

The dependency between indoor relative humidity and outdoor temperature of all the studied churches is shown on the left in Figure 2.15. The average RH of all unheated medieval churches during a one year period was 87%. The highest yearly average RH was measured in Ridala Church, 89% and lowest yearly average in Pöide Church, 85%. On the right in Figure 2.15 are the relative humidity values of different months. The average indoor RH of all churches in summer was 87% and in winter, 88%. The highest summer average RH was 90%, in Kaarma Church, and the lowest summer average was 84%, in Pöide Church. The highest winter average was 91%, in Valjala Church, and the lowest winter average was 85%, measured in Pöide Church. Differences between the studied churches are minimal. Most of the time, indoor RH in the studied churches is higher outdoor humidity, due to higher moisture content caused by the drying of the massive walls.

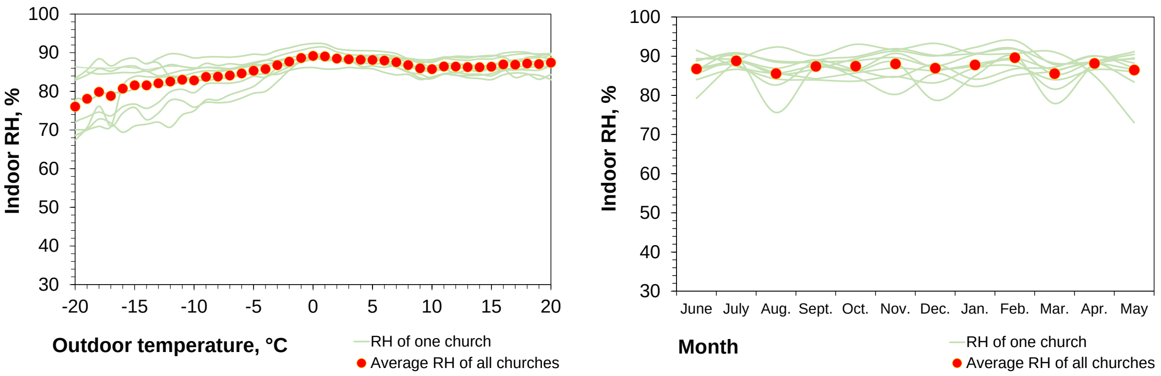


Figure 2.15 Dependency of indoor RH on outdoor temperature in all churches (left) and indoor RH conditions during the measurement period in all churches (right)

Conditions near organs were measured in seven unheated churches: Risti, Valjala, Püha, Kihelkonna, Karja, Karuse and Ridala. As organs are mainly influenced by relative humidity, the analysis of the suitability of indoor climate conditions is based on the probability of measurement results to deviate from the optimal conditions. Different authors have presented different optimal conditions for organs: Stadtmüller 1972: 60–70%, Supper 1967: 60%, Schlieder 1967 & 1969: 50–80%, Badertscher 1965: 45–65%, Hennings: 55–75%. Based on the values presented by Schlieder and Henning, the upper RH limit for organs is set to 80% and the lower limit is set to 55%. Another important factor for organs is the stability of RH. Too strong and too frequent fluctuations can cause the shrinkage and expansion of wooden details and may even lead to cracks.

Temperature and relative humidity conditions measured at one hour intervals inside the organ are shown on the left in Figure 2.16. On the right in Figure 2.16, temperature and RH measurements from data loggers located inside the organs of different churches are presented. The upper and lower limits for RH are based on literature and the mould risk curve is based on the model by Viitanen (Viitanen, 1997; Lähtesmäki et al, 2008).

From the left in Figure 2.16, it is clear that nearly all hourly measurements exceed the upper limit for relative humidity. The chart on the right in Figure 2.16 confirms the condition of unheated churches – organs in the churches are located in very damp conditions. However, relative humidity near the organ is relatively stable throughout the year without any strong fluctuations in RH.

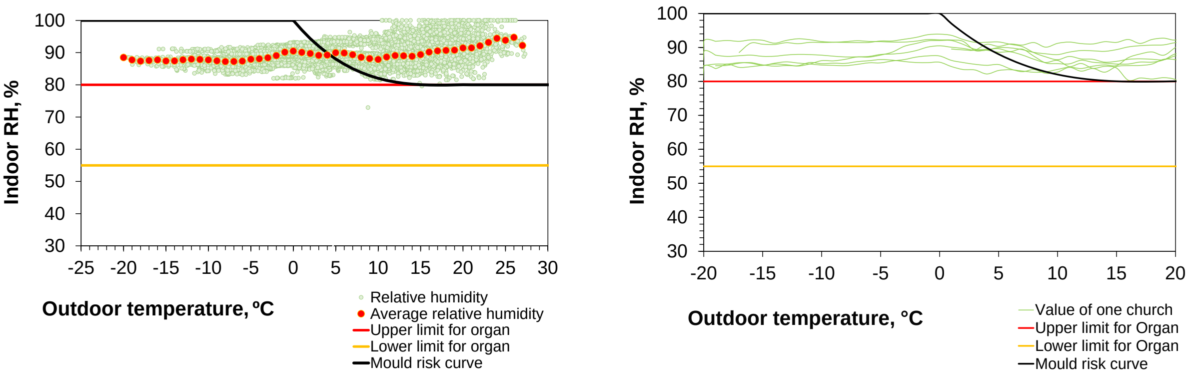


Figure 2.16 RH and temperature conditions near the organ in one unheated church (left) and average RH results of all studied churches (right)

Results from all the unheated medieval churches show that RH near the organ should be 5–15% lower if the risk limit is set to 80%. A high level of relative humidity carries a significant risk of mould growth. The risk of cracking due to excessive fluctuations of relative humidity is low in unheated churches.

2.3.3 Moisture Excess

Moisture content is not actively regulated in naturally ventilated unheated churches. Indoor water vapour content depends on moisture performance, ventilation and outdoor water vapour content. Indoor moisture load is defined by the difference between indoor and outdoor water vapour contents. The dependency between moisture excess and outdoor temperature with average values during a one year period in one studied unheated church is shown in Figure 2.17. It can be noted that when the outdoor temperature increases, then indoor moisture excess decreases – moisture content in outdoor air is higher than in indoor air. At cold temperatures, moisture excess is positive, which means that drying walls cause higher water vapour content indoors. The average monthly moisture excess is near 0 g/m^3 throughout the year with large over a one month period.

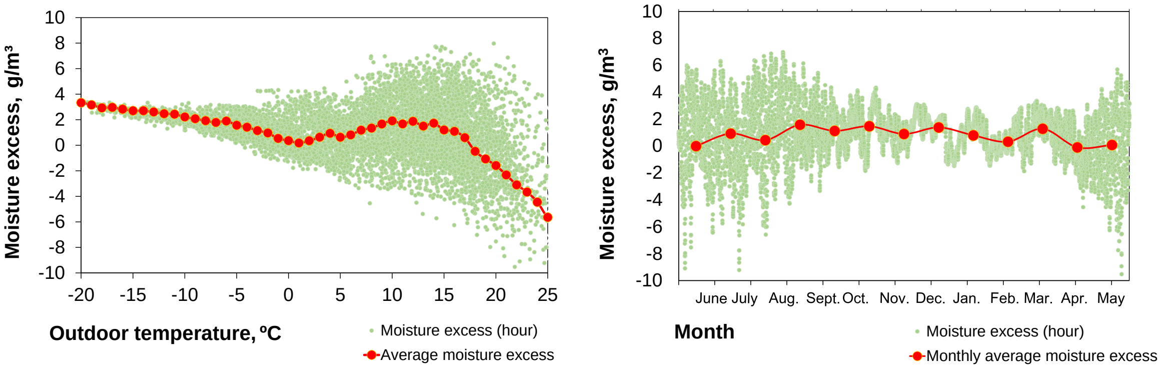


Figure 2.17 Dependency of indoor moisture excess on outdoor temperature in one church (left) and indoor moisture excess during the measurement period in one church (right)

The dependency between indoor moisture excess and outdoor moisture temperature in all studied churches is shown on the left in Figure 2.18. The average moisture excess of all unheated medieval churches during a one year period was 0.47 g/m^3. The highest yearly average moisture excess was in Ridala Church, 0.84 g/m^3, and the lowest yearly average was in Kaarma Church, 0.32 g/m^3. On the right in Figure 2.18 are shown the moisture excess values for different months. The average indoor moisture excess of all churches in summer was 0.43 g/m^3 and in winter, 0.48 g/m^3. The highest summer average moisture excess was 0.84 g/m^3 in Ridala Church and lowest summer average was 0.04 g/m^3 in Kihelkonna Church. The highest winter average was 0.83 g/m^3 in Ridala Church and lowest winter average was 0.22 g/m^3 in Pöide Church.

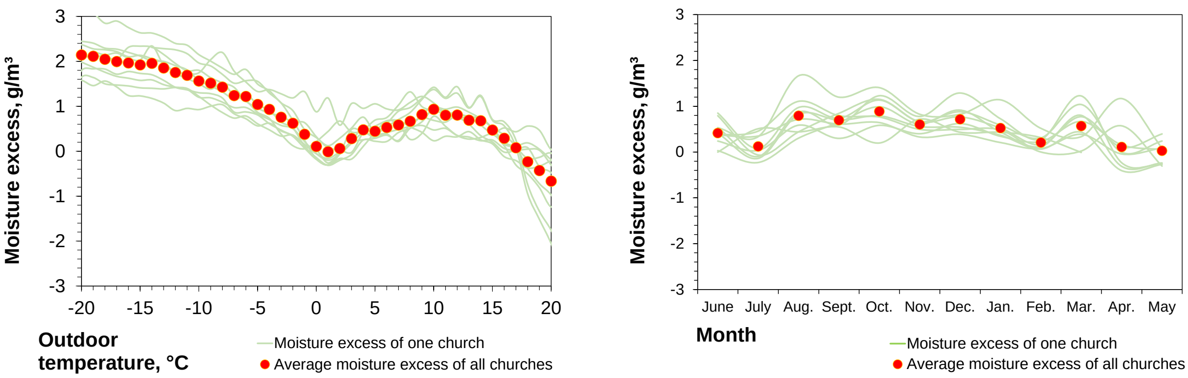


Figure 2.18 Dependency of moisture excess on outdoor temperature in all churches (left) and moisture excess during the measurement period in all churches (right)

2.3.4 Risk of mould growth

One of the most dominant problems caused mainly by moisture is mould growth. It occurs as a result of relatively high moisture concentrations. To evaluate mould growth risk on wooden details during the measurement period, a mould prediction model developed in Finland (Viitanen, 1997; Lähtesmäki et al 2008) was used. Relative humidity close to the surface is used to predict mould growth.

The evaluation of the risk of mould growth is based on indoor temperature and relative humidity. On the left in Figure 2.19, indoor temperature and relative humidity conditions in one unheated church are shown. It is clearly visible that when temperature is above zero, then most of the measurements are in the critical zone. On the right in Figure 2.19, the formation of the mould growth index is presented.

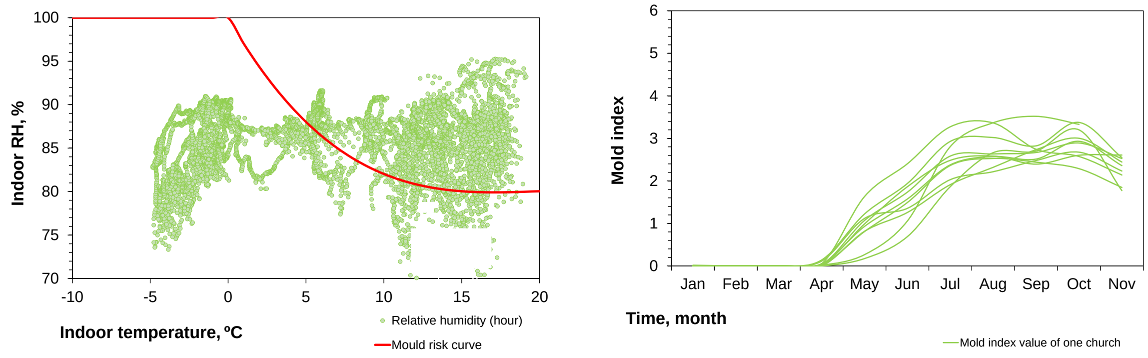


Figure 2.19 Indoor temperature and RH in one church (left) and change in mould growth index throughout the year (right)

Figure 2.19 left shows that the conditions are most suitable for mould growth in summer and autumn. In winter, the climate is too cold for mould to grow. In spring, indoor moisture content starts rising and the risk of mould growth reaches the highest level at the end of summer or in the beginning of autumn. As the walls of the churches have large hygroscopic mass, absorbed humidity stabilises the fluctuations of the water vapour content and drying walls ensure high RH during periods when temperature is stable or decline. In summer, the average mould index in all churches was 2.24 with maximum value of 3.01 in Püha Church and minimum value of 1.74 in Risti Church. In autumn, the average mould index of all churches was 2.68 with the maximum value of 3.42 in Valjala Church and minimum value of 2.19 in Kihelkonna Church.

Figure 2.20 confirms the mould index results. The average probability of all studied churches of suitable conditions for mould growth is 53% of the entire measurement period. Mould growth is the most likely in Valjala Church – 59% of the results from the entire measurement period exceeded the critical value. The lowest probability was found in Pöide Church where climate conditions facilitated mould growth for 45% of the measurement period.

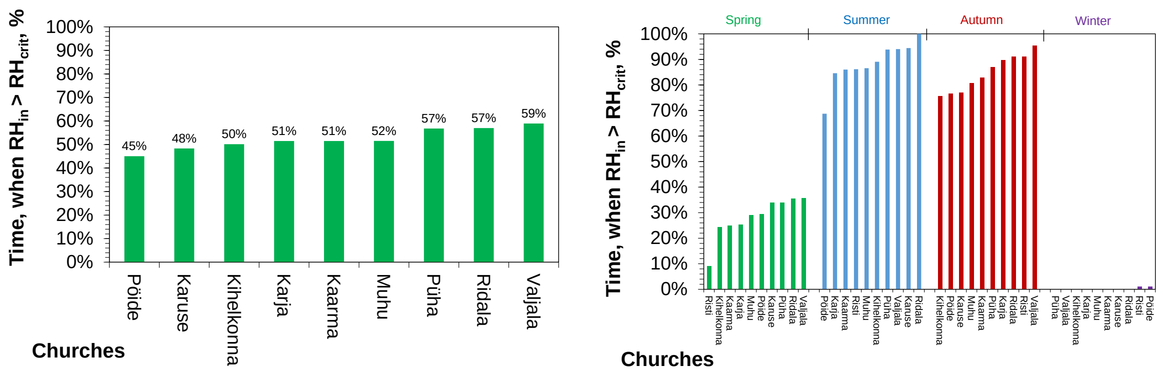


Figure 2.20 Favourable time in percent for mould growth throughout the entire measurement period (left) and favourable time for mould growth during four seasons (right)

Figure 2.20 right shows that in summer (June-August) and autumn (September – October), the risk of mould growth is significantly higher than in spring (March – May) and winter (December – February). However, it should be noted that in the spring and autumn periods, monthly differences in outdoor conditions are significant. Average probability of conditions facilitating mould growth in all studied churches is 28% in spring, 88% in summer, 85% in autumn and 0% in winter.

2.3.5 Stability of Indoor Climate

In addition to temperature and RH, the rate and extent of seasonal and daily/monthly fluctuations of temperature and RH plays an important role in the conservation of valuable historical interior objects, art treasures and organs. The daily and monthly amplitudes of temperature, relative humidity and indoor moisture excess are based on running average values of measurement results and were calculated in order to study the fluctuations of indoor climate parameters.

Temperature Stability

The dependency between the average daily amplitude of indoor temperature and daily average outdoor temperature of the entire measurement period is shown on the left in Figure 2.21. The average daily amplitude of indoor temperature in different churches remains between 0.1…3.0 °C, based on the daily average outdoor temperature. Inside a given day, the change of the indoor climate in the churches is small and slow with an average rate of temperature change of 0.05…0.10 °C/h. The dependency of amplitude of indoor temperature on the month is shown on left in Figure 2.21. In winter, the average daily amplitude of indoor temperature was 0.3…0.7 °C and in summer, 0.4…1.3 °C. The average daily amplitude of the entire measurement period was 0.6…1.1 °C.

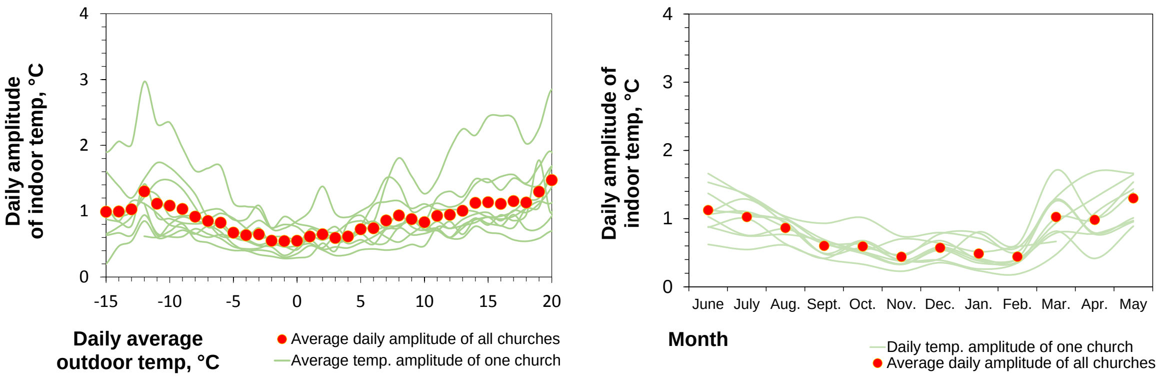


Figure 2.21 Dependency of the amplitude of average daily indoor temperature on daily average outdoor temperature amplitude (left) and dependency between daily temperature amplitude and month (right)

The dependency between average monthly amplitude of indoor temperature and monthly average outdoor temperature of the entire measurement period is shown on the left in Figure 2.22. Inside one month, the amplitude of indoor temperature in different churches fluctuates in the range of 2.4…10.9 °C, based on the monthly average outdoor temperature. When comparing Figure 2.22 with Figure 2.21, it is clear that monthly amplitude values are several times higher than daily values. In winter, the average monthly amplitude of indoor temperature in different churches was 4…7.5 °C and in summer, 3.3…5.4 °C. Average monthly amplitude of the entire measurement period was 4.4…6.8 °C.

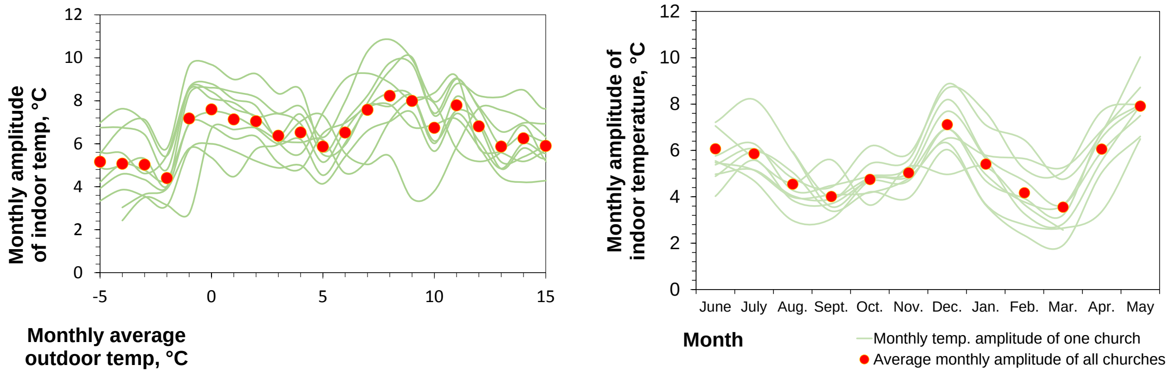


Figure 2.22 Dependency of the amplitude of average monthly indoor temperature on monthly average outdoor temperature (left) and dependency between monthly temperature amplitude and month (right)

Large differences in daily and monthly amplitudes show that changes in indoor temperatures take place slowly. Due to the large thermal mass of the walls, indoor climate does not respond to strong daily fluctuations in outdoor climate.

Stability of Relative Humidity

The dependency between average daily amplitude of indoor relative humidity and daily average outdoor relative humidity of the entire measurement period is shown on the left in Figure 2.23. Average daily amplitude of indoor RH in different churches remains in the range between 0.8…11.4%, based on daily average outdoor temperature. Inside a given day, the change in the indoor climate in the churches is small and slow, with an average rate of relative humidity change of 0.2…0.6%/h. The dependency of the amplitude of indoor RH on the month is shown in Figure 2.23 B. In winter, the average daily amplitude of indoor RH was 0.8…3.5% and in summer, 2.0…7.9%. Average daily amplitude of the entire measurement period was 1.9…6.2%.

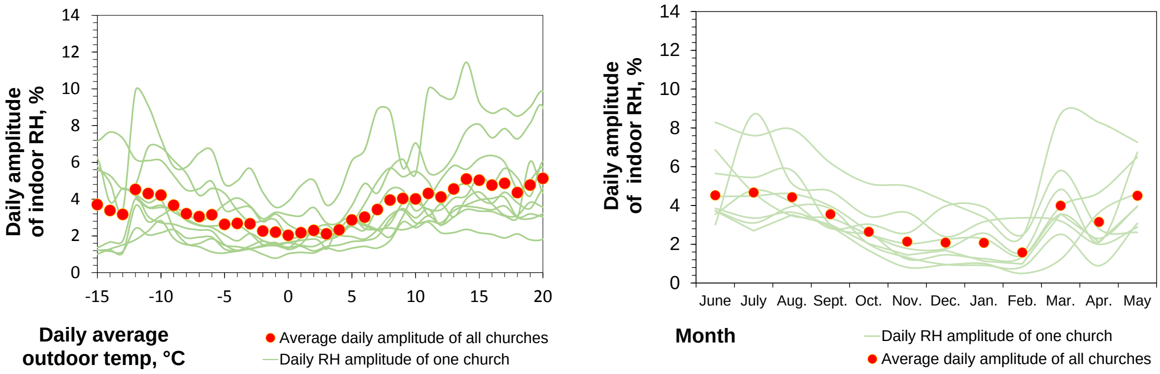


Figure 2.23 Dependency of the amplitude of average daily indoor relative humidity on daily average outdoor temperature (left) and dependency between daily amplitude of relative humidity and month (right)

The dependency between average monthly amplitude of indoor RH and monthly average outdoor temperature of the entire measurement period is shown on the left of Figure 2.24. On a monthly basis, the amplitude of indoor RH in different churches fluctuates in the range of 6…38%, in correlation with the monthly average outdoor temperature. When comparing Figure 2.24 with Figure 2.23, it can be noticed that monthly amplitude values are several times higher than daily values. In winter, the average monthly amplitude of indoor RH in different churches was 7…24% and in summer 10.0…21%. The average monthly amplitude of the entire measurement period was 11…26%.

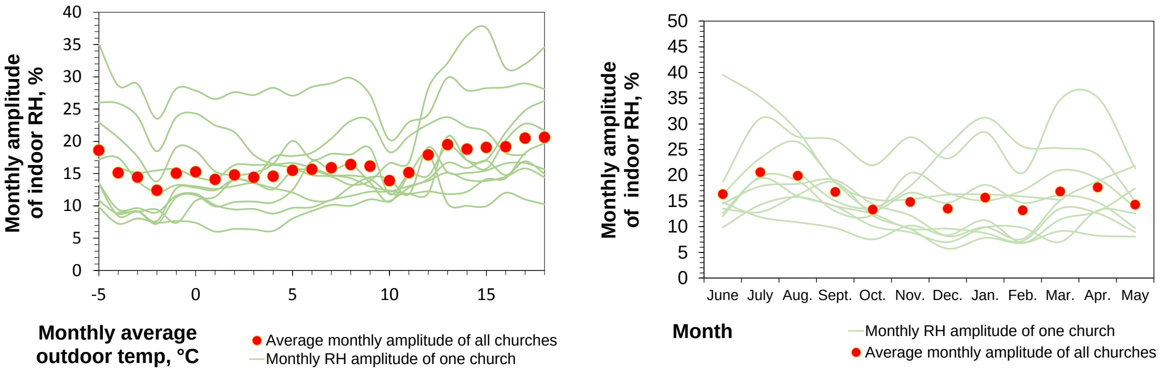


Figure 2.24 Dependency of the average monthly amplitude of relative indoor humidity on monthly average outdoor temperature (left) and dependency between monthly amplitude of relative humidity and month (right)

The relatively large differences in amplitude between the churches are related to their different state of repair and different usage. The higher the amplitude of relative humidity, the greater the influence of outdoor conditions. Badly sealed churches have a more intensive air exchange with the outdoor environment. This is caused by cracks and gaps in the building envelope, as well as open doors and windows.

Stability of moisture content

The dependency between the average daily amplitude of indoor moisture content and daily average outdoor temperature of the entire measurement period is shown on the left in Figure 2.25. Average daily amplitude of indoor moisture content in different churches is in the range between 0.1…2.8 g/m^3, based on daily average outdoor temperature. Inside a given day, the change of the indoor climate in the churches is small and slow, with an average rate of moisture content change of 0.04…0.06 g/m^3 per hour. The dependency of the amplitude of indoor moisture content on the month is shown on the left in Figure 2.25. In winter, the average daily amplitude of indoor moisture content was 0.10…0.29 g/m^3 and in summer, 0.58…1.0 g/m^3. Average daily amplitude of the entire measurement period was 0.41…0.73 g/m^3.

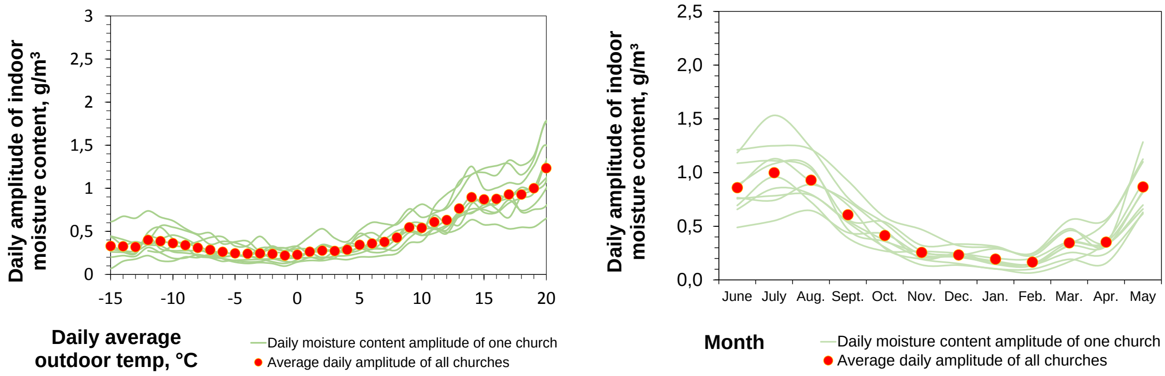


Figure 2.25 Dependency of the amplitude of the average daily indoor moisture content on daily average outdoor temperature (left) and the dependency between daily indoor moisture content amplitude and the month (right)

The dependency between the average monthly amplitude of indoor moisture content and monthly average outdoor temperature of the entire measurement period is shown on the left in Figure 2.26. Inside a month, the amplitude of indoor moisture content in different churches fluctuates in the range of 0.8…7.9 g/m^3, based on the monthly average outdoor temperature. When comparing Figure 2.26 with Figure 2.25, it is clear that monthly amplitudes are several times higher than daily values. In winter, the average monthly amplitude of indoor moisture content in different churches was 1.48…2.95 g/m^3 and in summer, 3.30…4.96 g/m^3. Average monthly amplitude of the entire measurement period was 2.83…4.39 g/m^3.

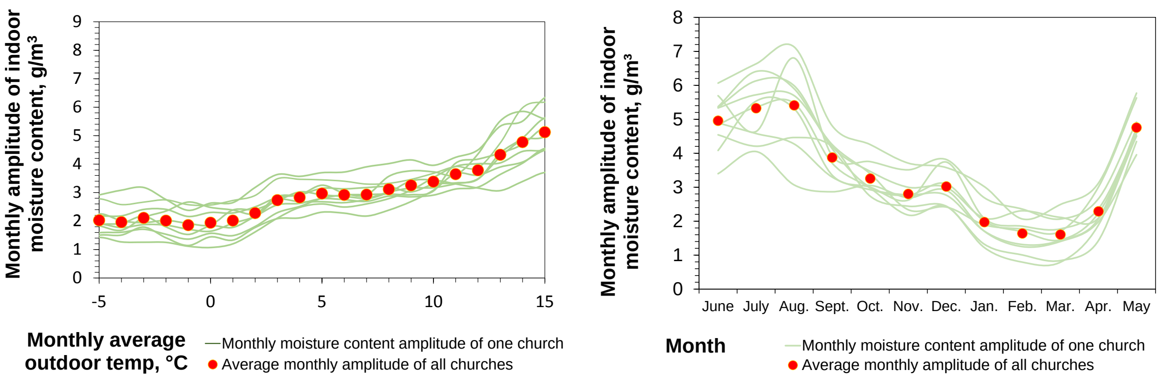


Figure 2.26 Dependency of the amplitude of average monthly indoor relative humidity on monthly average outdoor temperature (left) and the dependency between monthly amplitude of relative humidity and the month (right)

Wood fracturing

Mechanical degradation is mostly related to changes in relative humidity and less to changes in temperature. The main result of RH differences is the change in the dimensions of materials caused by the fluctuation of equilibrium moisture content (Martens, 2012). Indoor climate fluctuations play an important role in damage to objects. However, not all fluctuations cause similar damage. Fluctuations with a duration of under one hour do not affect most of the church`s objects at all (Michalski 1993). The outer layer of wooden objects responds faster to the RH change than the object as a whole and if the fluctuation causing strain in the object is shorter than the object`s response time, then the object will not react to that change. Fluctuations lead to deformation if the fluctuation lasts longer than the object`s response time and the strain induced is larger than the strain at yield point.

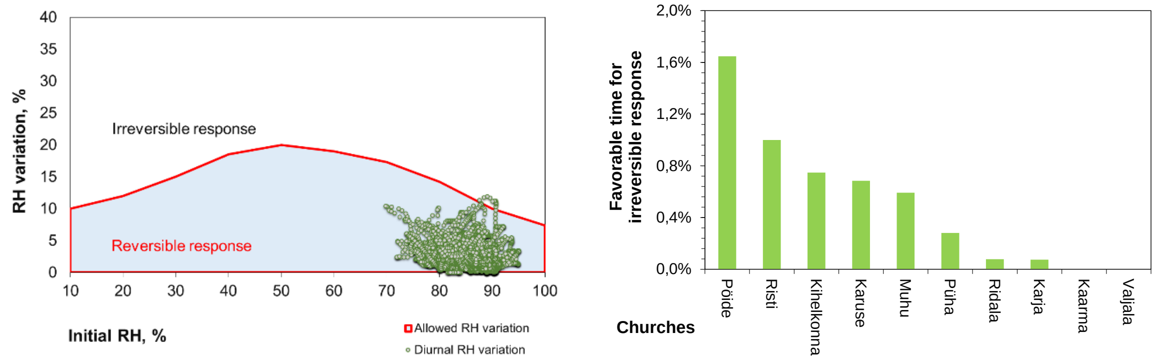


Figure 2.27 Variations in relative humidity in one unheated church compared to the range of reversible and irreversible response of wood (left) and time when the conditions are facilitating irreversible response occurrence in wooden objects (right)

On the left in Figure 2.27, the range of variations in relative humidity in one unheated church is presented. Based on the risk boundary for irreversible response in the object, the percentage crossing this line was calculated. Results are show on the right in Figure 2.27. It can be noted that conditions facilitating irreversible response in wooden sculptures make up around 0…1.6% of the yearly measurement results. Indoor climate conditions are in the safe range for most of the year. Risk in Pöide is higher than other churches because of repairs taking place which caused higher amplitudes in daily RH fluctuations.

Besides wooden sculptures, it is also important to study how fluctuations in relative humidity influence panel paintings. The painted layer on wood experiences stresses due to the mismatch in the dimensional response of gesso and wood (Martens, 2012). If uncontrolled changes in moisture related strain cross the critical level, the gesso can crack or delaminate. The analysis of panel paintings is based on the allowed RH variations which do not cause damage to gesso on lime wooden panels 10 mm thick during a period of 100 years. It should be noted that the method for defining critical RH fluctuations is generally based on changes in RH around 50%. In the studied churches, the yearly average relative humidity fluctuates, dependent on church, in the range between 84 to 89%. For the analysis, relative humidity cycles of 1, 7 and 30 days were chosen.

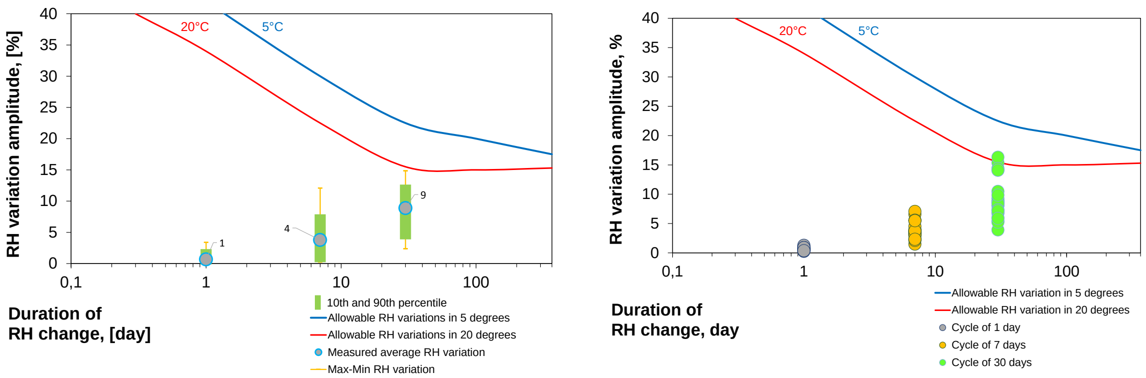


Figure 2.28 Characteristics of the amplitude of RH variation in one church dependent on the duration of cycle (left) and average RH variation amplitudes of all measured churches (right)

On the left in Figure 2.28, the situation of one church is presented. Average amplitude depended on the different duration of RH cycles, average and maximum amplitude and 10th and 90th percentile are shown. The boundaries for critical amplitude of 20 °C and 5 °C show the critical values for RH fluctuations in different temperatures.

On the right, it can be noted that RH variations fall mostly in the safe range. As temperature and RH changes are very slow and small, there are practically no fluctuations critical for panel paintings on a daily, weekly or monthly basis. Only the conditions in Pöide Church crossed the critical curve for 11% of measurement period, but the repair works in the church played a great role in these fluctuations. However, this analysis is not absolutely accurate, because the model is mainly based on RH fluctuations around 50%.

2.3.6 Spatial distribution of indoor climate in churches

The distribution of the temperature and relative humidity was mapped in Muhu, Risti, Kaarma and Valjala Churches in June 2012. Results from Risti and Muhu Churches are presented below.

In Muhu Church, an up to 0.7 °C difference in indoor temperature was measured: the chancel was the warmest (+14.3 °C) and the coolest place (+13.6 °C) was located near the northern facade. The difference in relative humidity was 4%. The highest (84%) relative humidity was measured near the northern facade and the lowest (80%) in the south eastern corner. The average outdoor temperature of the preceding day was 16 °C and RH 71%.

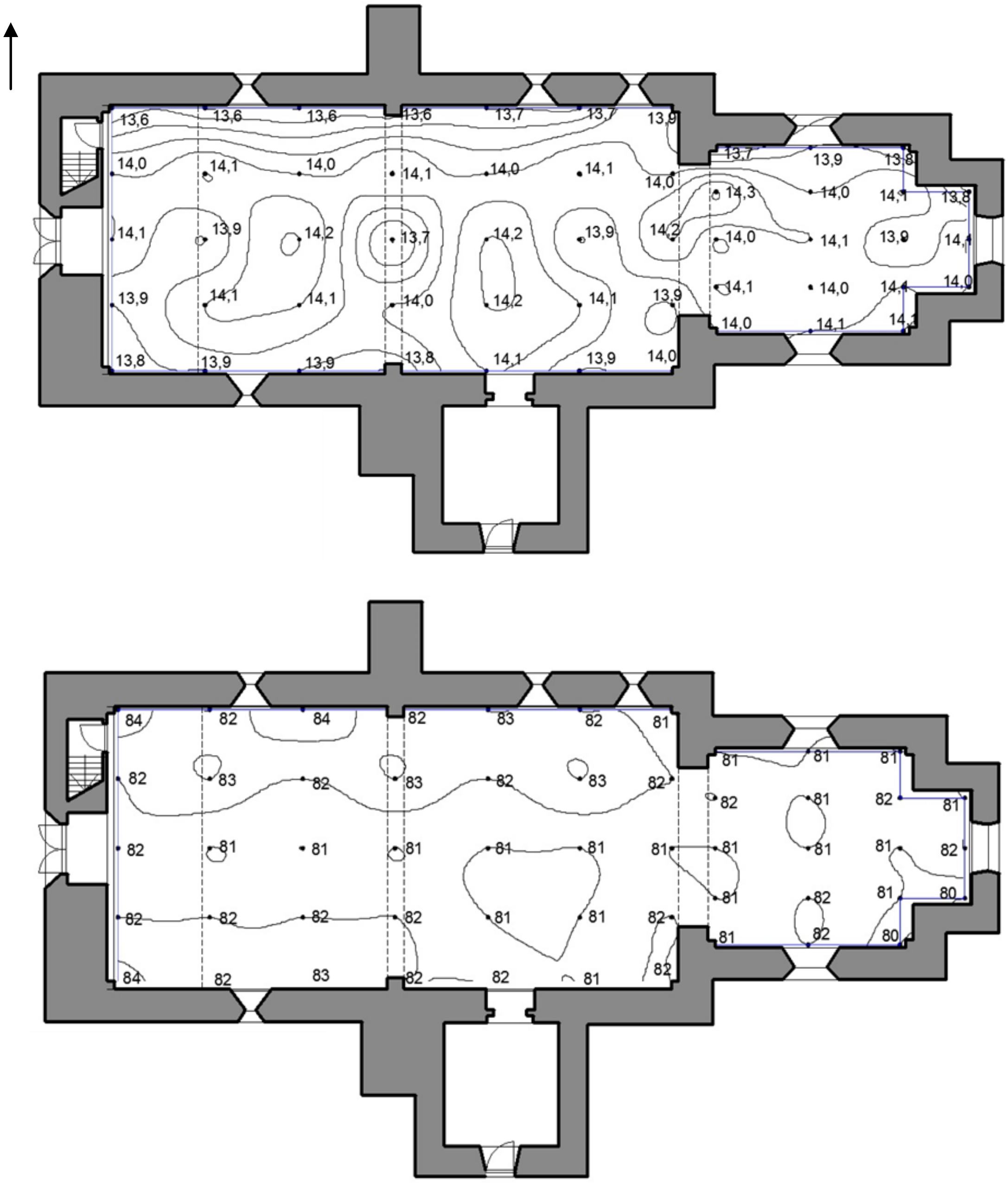


Figure 2.29 Spatial distribution of indoor temperature (upper) and RH (bottom) in Muhu Church in June 2012

In Risti Church, an up to 1.5 °C difference in indoor temperature was measured: the warmest (+18.0 °C) temperature was measured near the south eastern façade and the coolest (+16.5 °C) near the entrance. The difference in relative humidity was 8%. The highest (83%) relative humidity was measured near the eastern corner of hall and the lowest (75%) in the eastern corner behind altar. The lines were more intense behind altar due to the sun that shined in through window. Average outdoor temperature on the preceding day was 17.7 °C and RH 73%.

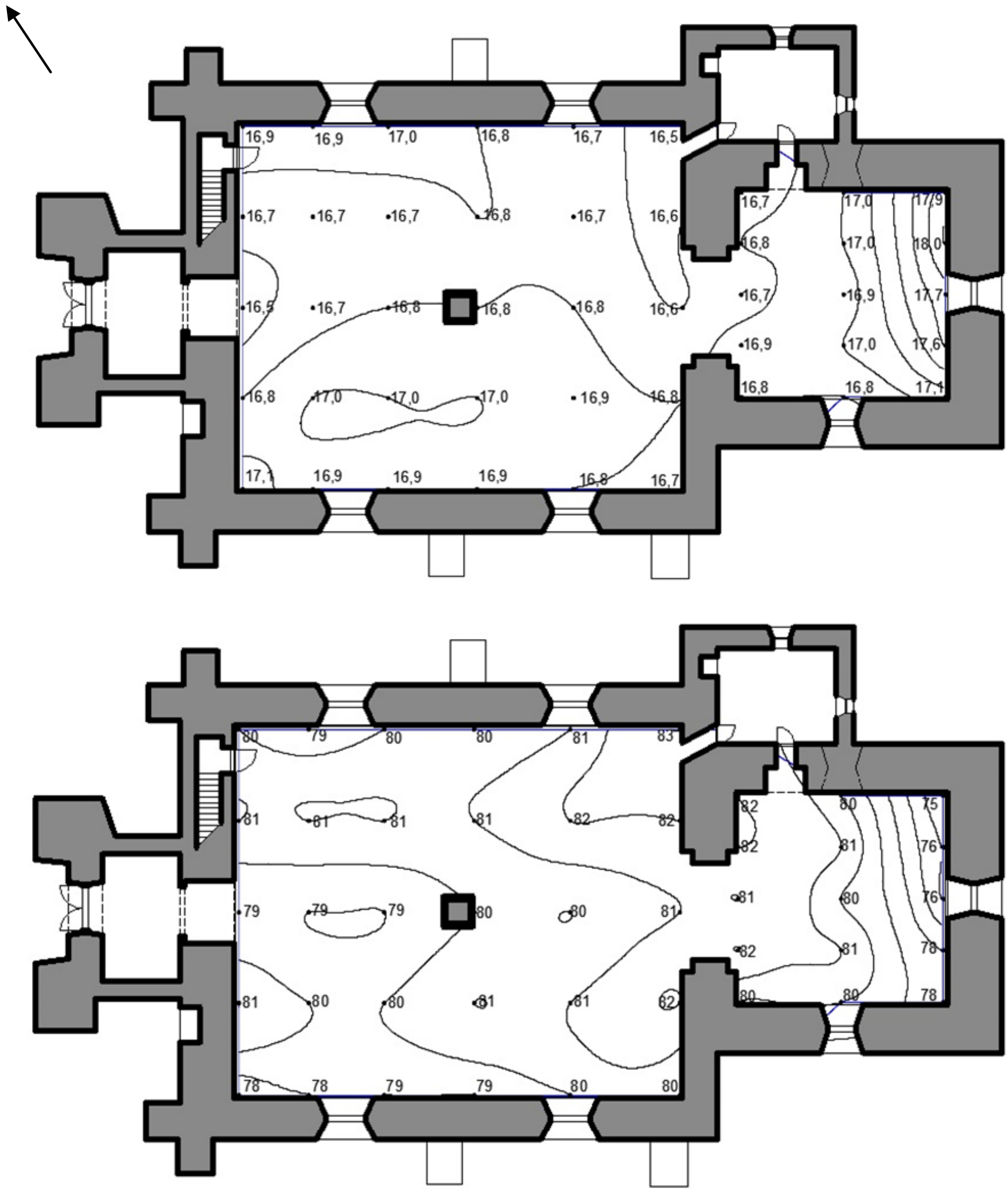


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Figure 2.30 Spatial distribution of indoor temperature (upper) and RH (lower) in Risti Church in June 2012

When comparing the two different churches, it can be noted that the spatial distributions of temperature and relative humidity are mostly steady in both cases. In Risti Church, sun caused more intense variations in temperature and RH lines behind the altar but the overall conditions are stable.

2.3.7 Requirements for changes in indoor climate

As all the studied churches were unheated, thermal comfort was not assessed. Indoor relative humidity and temperature conditions in unheated churches should be suitable for the most valuable parts of the interior: organ, altar, pulpit and paintings. The results showed that main problem in unheated churches is the risk of mould and algae growth. Relative humidity in unheated churches is generally over 80%, an extremely critical level for mould growth and risk of condensation. In order to reduce the mould risk, relative humidity should be maintained below 80% or even lower.

Too high RH in churches is not the only risk. It is important to maintain RH values higher than 55%. It is important to follow these criteria when deciding to reduce the relative humidity levels. Too low RH causes shrinkage of wood and leads to cracking in wooden details.

When reducing the RH in churches, it is also important to control the fluctuations. Measurement results showed that due to slow changes in indoor climate, RH amplitudes are mostly in the safe range, but there are still some cases when the conditions cross the critical line (see Wood fracturing). It is suggested to keep RH fluctuations inside 10% over one day and RH fluctuations over a period of one year inside 30%, between about 50 to 80% RH (Table 2.1**Error! Reference source not found.**). On a daily basis, RH variations were in the range of 1.9…6.2% and on a monthly basis, 10.7…26.4%. Too high monthly amplitudes lead to fluctuations of over 30% over one year which means that yearly amplitudes of RH fluctuations in unheated churches should be reduced and maintained. Suitable conditions for indoor objects can be developed when lowering absolute RH levels below 80% and avoiding too high amplitudes in RH changes.

2.4 Discussion

The correspondence for mechanical degradation risk was based on the object`s response to RH. The response time of RH changes for panel paintings was defined to be 4.3 days and for wooden sculptures, 10 hours (ASHARE, 2011). Evaluation of the risk of irreversible response to RH changes in objects is based on a diurnal relative humidity fluctuation cycle. Most of the measurement results showed that there is no risk for irreversible response. However, the evaluation was based on daily amplitudes where changes in indoor climate were very low. The method of analysis for slow changes in RH over a one month period should be developed and a risk assessment based on monthly cycle amplitudes of RH would probably present other results.

The analysis of cracking in the gesso layer was based on fluctuations during the hourly, daily and monthly cycle. The results showed that there is practically no risk of panel paintings cracking because of the longer response time of the wood due to the painting layer. However, this analysis method is mainly accurate for changes in RH that take place around 50% RH and the results from this study might differ slightly from the actual situation.

The results showed that relative humidity is very high in churches throughout the year, mostly over 80%. These conditions create a high risk for mould growth and biological degradation. When deciding to reduce the RH levels, its influence one the fluctuations in RH should be studied. Depending on the method – heating, dehumidifying or using adaptive ventilation – the fluctuations in indoor RH differ and for sustainability, the amplitudes should be low.

2.5 Conclusions

Indoor climate conditions were analysed in ten naturally ventilated unheated Estonian churches in order to get an overview of the present situation and find solutions to problems and risks that need to be reduced. The climate analysis was based on one year's (June 2012 to May 2013) measurements of air temperature and relative humidity.

During the whole survey period, the yearly average indoor temperatures of unheated churches were in the range of 6.3…7.6 °C with the average value of all churches being 6.9 °C. The average indoor temperature in summer was 15.4 °C or in the range of 14.5…16.1 °C and in winter, -1.0 °C or in range of -2.2…0.3 °C. Differences in yearly average temperatures were very small and indoor climate responds very slowly to outdoor changes.

The average relative humidity in all unheated churches during a one year period was 87.1%, in the range of 84.6…89.1%. Average value in summer was 86.9%, in the range of 84.0…89.5% and in winter 87.7%, in the range of 84.5…91.4%. Most of the time, indoor RH in studied churches is higher than outdoors due to higher moisture content caused by the drying massive walls. A high level of relative humidity creates a significant risk of mould growth. The average probability in all studied churches of conditions facilitating mould growth was 53% or in the range of 45%...59%. The risk of mould growth was the highest in summer months when an average of 88% of measurement results crossed the critical curve. The risk was the lowest in winter months when there were practically no conditions facilitating mould growth.

Relative humidity near organs was assessed in more detail. According to literature, the level of RH near organ should be between 55% – 80%. Results showed that relative humidity near organs is higher than 80% for most of the time.

Indoor moisture load was defined by the difference between indoor and outdoor water vapour content. The average moisture excess of all unheated churches during a one year period was 0.47 g/m^3 or in the range of 0.32…0.84 g/m^3. The average value in summer was 0.43 g/m^3 or in the range of 0.04…0.83 g/m^3 and in winter 0.48 g/m^3 or in the range of 0.22…0.83 g/m^3. A low moisture excess show that air exchange between indoor and outdoor environment balances the amounts of indoor and outdoor moisture content.

In addition to the average values of indoor climate parameters, their fluctuations were studied. The average rate of temperature change in churches was 0.05…0.10 °C/h. In winter, the average daily amplitude of indoor temperature was 0.3…0.7 °C and in summer, 0.4…1.3 °C. The average daily amplitude of the entire measurement period was 0.6…1.1 °C. The average monthly amplitude of indoor temperature in winter months in different churches was 4…7.5 °C and in summer, 3.3…5.4 °C. The average monthly amplitude of the entire measurement period was 4.4…6.8 °C.

The average rate of relative humidity change in churches was 0.2…0.6%/h. In winter, the average daily amplitude of indoor RH was 0.8…3.5% and in summer, 2.0…7.9%. The average daily amplitude of the entire measurement period was 1.9…6.2%. The average monthly amplitude of indoor temperature in winter months in different churches was 6.8…24% and in summer, 10…21%. The average monthly amplitude of the entire measurement period was 10.7…26.4%.

The average rate of indoor moisture content change in churches was 0.04…0.06 $(g/m^3)/h$. In winter the average daily amplitude of indoor moisture content was 0.10…0.29 g/m^3 and in summer, 0.58…1.0 g/m^3. The average daily amplitude of the entire measurement period was 0.41…0.73 g/m^3. The average monthly amplitude of indoor temperature during winter months in different churches was 1.48…2.95 g/m^3 and in summer, 3.30…4.96 g/m^3. The average monthly amplitude of the entire measurement period was 2.83…4.39 g/m^3.

Mechanical degradation of indoor objects is manly caused by fluctuations in relative humidity. In this study, the irreversible damage risk of wooden objects and the cracking risk of the gesso layer of panel paintings due to RH fluctuations were studied. The results showed that there are only a few percent of the measurement result cross the critical line. Conditions facilitating irreversible response in wooden sculpture make up about 0…1.6% of the yearly measurement results. The analysis of the cracking risk of the gesso layer showed that conditions exceed the critical line only in one church where repair works took place that played an important role in RH fluctuations.

The spatial distribution of indoor temperature and RH was analysed in two churches. The results showed that distribution was even and differences of different parts of the church building were small.

The main conclusion of the study should be that the greatest risk related to indoor climate in naturally ventilated unheated medieval church is high relative humidity. In order to reduce the risk of mould and algae growth, relative humidity should be decreased by about 20% and amplitudes of RH fluctuations must be kept below 30% inside a year.

2.6 Acknowledgements

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3 OVERVIEW OF AIR INFILTRATION IN THE STUDIED CHURCH BUILDINGS

Alan Väli, Targo Kalamees

3.1 Introduction

Air exchange in unheated churches is generally controlled by natural ventilation: passive stack ventilation and window leakage. The height of the churches causes positive air pressure at the ceiling level and negative pressure at the floor level. Positive air pressure may cause the convection of moist air to the roof structures and ceiling and negative air pressure may cause soil diffusion into the building.

Low airtightness of the building envelope leads to uncontrolled airflow between the indoor and outdoor environments through cracks and holes. Air infiltration and its influence on indoor climate depends on the airtightness of building envelope, the locations of the leaks, the differences between indoor and outdoor air pressure, building materials and climate conditions. The differences in air pressure on different sides of building envelope are caused by wind, differences in temperature or ventilation.

A too high air infiltration rate may cause several problems in churches:

- variations in indoor climate due to outdoor climate;
- higher energy use if the church is climate controlled;
- air pollution and unwanted smells spreading indoors.

Research topics in this study included:

- overview of the situation: leakage rate, leakage places;
- comparison of measurement methods (common blower door, PFD, Pulse);
- data for indoor climate and energy simulations.

3.2 Methods

The infiltration and ventilation measurements were performed using two different methods:

- fan pressurization method (EN 13829)
- tracer gas method.

3.2.1 Fan pressurization method

This technology was used in five different churches:

- St Catherine`s Lutheran Church in Muhu
- St Martin`s Lutheran Church in Valjala
- St James`s Lutheran Church in Püha
- St Peter`s and Paul`s Lutheran Church in Kaarma
- Lutheran Church of the Holy Cross in Risti

Fan pressurization tests in churches of Saaremaa were carried out in the beginning of July 2012 and in Harju-Risti October 2013. The Blower Door is a special diagnostic tool that is used to pressurize or depressurize the building and measure its airtightness. The metering device (Minneapolis Blower Door Model 4: measurement range in 50 Pa is 25 m^3/h…7800m^3/h, accuracy +- 3%) consists of an airtight fabric, fan speed controllers and a fan placed in an adjustable frame (Figure 3.1)

Figure 3.1 Air leakage measurements with one (left) and two ventilators (right)

The air leakage test was performed according to the standard EVS EN 13829. The device was temporarily sealed in an exterior door frame and all other doors and windows were closed during the test. In some churches, it was necessary to use two devices in parallel in order to achieve a higher air pressure difference between indoor and outdoor air.

The fan was used to create differences of air pressures between the indoor and outdoor environment. During the test, the airflow that was needed to maintain the air pressure difference was measured. The same amount of air that was blown through the blower door fan came into the church through cracks and holes. The goal was to achieve a pressure difference of 50 Pa inside and outside, but due to the unsealed envelopes and large volume of the churches, a difference of about 15…37 Pa was the maximum achieved. A 50 pascal pressure is roughly equivalent to the pressure generated by a 8.9 m/s wind blowing on the building from all directions. Airflow at 50 Pa was read from the trend line plotted on the bases of measurement results (Figure 3.2)

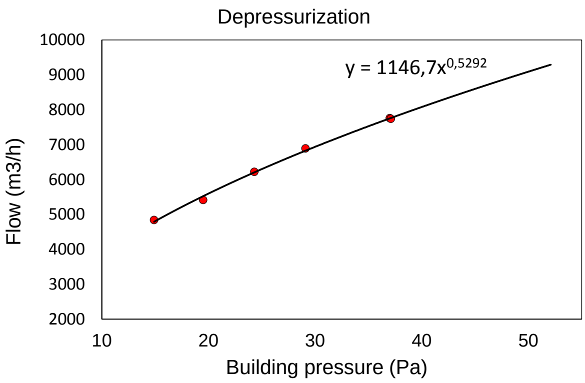

Figure 3.2 Measurement results from the Blower Door test with the plotted trend line

The airtightness of a church's envelope is characterized by two parameters:

- q_{50} – air leakage rate at 50 pascals per unit of envelope area (unit: $m^3/(h \cdot m^2)$). This parameter was calculated by dividing the measured air leakage at 50 pascals by the envelope area of the church.
- n_{50} – air exchange per hour at 50 pascals (unit: 1/h). This parameter was calculated by dividing the measured air leakage at 50 pascals by the volume of church.

3.2.2 Tracer Gas Method

With this technique, it is possible to study the supply rate and distribution patterns of supplied air from the outside to different areas or the whole building.

For the study, 11 tracer gas sources were used in in the hall of the church. One gas source was used in the sacristy and one in the porch room with tracer gas emission rates adjusted to the room volumes to ensure homogenous emission to the whole building. The tracer gas diffuses out of the sources at a known constant rate and is mixed into the room air. The resulting tracer gas concentration in different parts of the building or room depends on the ventilation of the rooms. The tracer gas concentration in different parts and locations was measured using a passive sampler. Similar techniques for measuring air exchange in naturally ventilated churches have also been used in other studies.

Figure 3.3 Tracer gas source and absorber in the church

3.3 Results

The results of the fan pressurization tests are presented in Table 3.1. Air leakages were measured in five churches and the average air leakage rate at 50 pascals q_{50} was 12.3 $m^3/(h \cdot m^2)$. The average air exchange rate per hour at 50 pascals n_{50} was 6.4 1/h.

The differences between the highest and lowest values are significant. These are mainly related to the different condition of the churches, because the four churches in Saaremaa were measured on the same day with mostly identical outdoor climate conditions.

Table 3.1 Air leakage measurements with fan pressurization method.

Church	Volume, m^3	Area, m^2	q_{50}, $m^3/(h \cdot m^2)$	n_{50}, 1/h
Kaarma	4082	1942	23	11
Valjala	3032	1623	14	7.6
Püha	1793	1049	9.1	5.3
Risti	2330	1180	8.3	4.2
Muhu	2315	1292	6.8	3.8

Table 3.1 shows that a larger volume or area does not necessarily mean higher air leakage rates. It is also clear that the air leakage rate at 50 pascals per unit of envelope area is higher than air exchange per hour at 50 pascals. The reason for that is the compactness of the churches, which is dependent on the church`s floor plan. In the studied churches, the volume is 50…58% bigger than the envelope area.

In Table 2.2, the measurement results of the tracer gas technique used in Risti Church are presented. Measurements were performed with window airing (April – May) and with the doors and windows closed (March – April; February – March).

Table 3.2 Air leakage measurements using the tracer gas technique

Parameter	April – May	March – April	February – March
Airing	Yes	No	No
Indoor temp, °C	7.1	-0.3	0.7
Outdoor temp, °C	8.3	1.9	-5.9
Temp difference, °C	-1.2	-2.2	6.6
Wind, m/s	3.2	2.8	3
acr, 1/h	0.61	0.26	0.34

From Table 3.2, it can be seen that due to the opened doors, air exchange rate in April–May was about 2 times higher than in colder periods. Wind speed was between 2.8…3.2m/s. When comparing the measurements from 2010 and 2013, it can be noted that in 2010, the temperature difference between indoor and outdoor environment was -2.2 °C (indoor temperature was higher than outdoors) and in 2013, the difference was 6.6 °C. At the same time, the air exchange rate was only 0.08 1/h higher in 2013. Based on the results, it can be stated that differences between indoor and outdoor temperature do not influence air infiltration very much.

The main sources of air leakage were the holes and gaps in arches, broken panes of windows and cracks around doors (Figure 3.4).

A B C D

Figure 3.4 A: Ventilation holes in arches
B: Broken window panes
C: Cracks around windows
D: Cracks around doors

Holes in arches mostly influence air leakage rates when the temperature indoors is higher than outdoors. Warmer air moves up and leaves through gaps. When envelope temperature is very low and indoor RH is high, it can lead to condensation and algae growth around holes. Broken and cracking windows or doors also cause a high condensation risk and allow snow to drift into the church during winter. Melting snow causes algae growth.

3.4 Discussion

The results showed that there are big differences between the highest and lowest values of air leakages. In order to make more accurate conclusions about the overall situation of air infiltration in unheated churches, more measurements should be carried out.

The tracer gas method was only used in Risti Church. In order to compare different churches, more similar investigations should be performed. In the present situation, the results showed that when the indoor temperature is 6.6 °C warmer than outdoors, the air exchange rate is 0,08 1/h higher than in the situation when the indoor temperature is 2.2 °C colder than outdoors. In order to get more accurate results about its influence on temperature, a measurement period with higher difference in temperature should be chosen.

If there are holes and gaps in the building envelope, windy weather can directly influence the indoor climate. In the present study, wind speed was mostly the same (2.8…3.2 m/s) in all measurement periods. As wind speed greatly influences air leakages, a period with stronger winds should be chosen for a comparison with calm periods.

When deciding to fix all holes and gaps, it is important to study its influence on moisture regime. Moisture leaves the church through cracks and when these are sealed, the indoor moisture load will grow. As average level of RH is very high as it is, closing gaps and cracks may lead to a high risk of condensation and algae.

3.5 Conclusions

Air leakages were measured in five churches using the blower door test and using the tracer gas technique in one church. The average air leakage rate at 50 pascals q_{50} was 12.3 $m^3/(h{\cdot}m^2)$ with a maximum value of 23 $m^3/(h{\cdot}m^2)$ and a minimum value of 6.8 $m^3/(h{\cdot}m^2)$. The average air exchange rate per hour at 50 pascals n_{50} was 6.4 1/h with a maximum value of 11 1/h and a minimum value of 3.8 1/h. The large differences show that churches are in a largely different technical condition.

The tracer gas test was carried out in three different periods: April – May; March – April, and February – March. The measured air exchange rate per hour was 0.61 1/h, 0.26 1/h and 0.34 1/h, respectively. The results showed that small differences between indoor and outdoor temperatures do not influence air infiltration very much.

The main sources of leakages were the holes and gaps in arches, broken window panes and cracks around doors.

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The authors are grateful to Paul Klõšeiko, Simo Ilomets, Margus Napp, Endrik Arumägi, Jaanika Saar, Üllar Alev from Tallinn University of Technology for the help with the measurements.

4 BIODETERIORATION, SALT DISTRIBUTION AND DAMAGE TO PLASTER AND RENDER / EXTENT AND REASONS FOR SALT, MOULD AND ROT DAMAGE

Urve Kallavus

4.1 Research questions

Biodeterioration research combines different approaches for the evaluation of the state of different kinds of materials. The focus of this study is on the evaluation of the state of stone wall surfaces and wooden structures in Estonian medieval churches. In particular, the survey concentrates on the following subjects:

- Tape lift sampling used for determining the organisms living on the surfaces of structural elements, plaster and interior
- Sampling of plaster, stone and finishing materials to study the localisation of microorganisms and their destructive effect on the surface and the inside of stone surfaces
- Testing wood samples to establish the kind of wood rot
- Establishing the connection between biofilm components and surface colouration

4.2 Introduction

Medieval churches were built with massive stone walls. A stable indoor climate has developed with slow changes in temperature and humidity. The indoor climate of unheated churches is mainly determined by the outdoor climate which is not very favourable. Long term high moisture content in the walls causes both physical and biological destruction of the surface layers (plaster) as well as the inner structure. The biological influence (biodeterioration) on the stone wall surfaces is described as biofilm activity.

4.2.1 Biofilm

Biofilm can be formed by a single bacterial species, but more often, biofilms consist of many species of bacteria, as well as fungi, algae, protozoa, debris and corrosion products. Essentially, biofilm may form on any surface exposed to bacteria and some amount of water or 100% air humidity. Aeroterrestrial microalgae typically form the interface between all kinds of hard substrata and the atmosphere in biofilms. High air humidity or the presence of water is the prerequisite for optimum photosynthesis and growth of aeroterrestrial microalgae. However, when dried and consequently inactive, these microorganisms can recover quickly if water becomes suddenly available.

Not all microorganisms observed on building materials are identified, but fungi (including yeasts), algae (including diatoms), and bacteria (including actinomycetes and cyanobacteria) are the most frequently studied.

4.2.2 Substrate

Biofilm can attach to various types of substrates. The substrate surface can be of natural origin, e.g., tree barks, soil, and rocks, or of artificial origin, e.g., roof tiles, concrete, or building facades. On man-made surfaces, aeroterrestrial microalgae often cause aesthetically unacceptable discolouration known as incrustations and patinas.

4.2.3 Algae

Algae are a very large and diverse group of simple, typically *autotrophic* organisms. It means that they are able to make their own food and do not need a living source of energy or organic carbon. They use energy from light (photosynthesis) or inorganic chemical reactions (chemosynthesis). Most are photosynthetic. A few species of algae are able to grow in the surface layer of soil, on trees and stones (Graham 2008).

There are no specific algae species growing only in Estonia. One common alga on old stone walls is the unicellular *Pleurococcus.* Necessary conditions for living include moisture, air and light.

4.2.4 Fungi

Fungi are a kingdom of heterotrophic single-cell, multinucleated or multicellular organisms including yeasts, moulds, and mushrooms. Unlike algae or plants, fungi lack the chlorophyll necessary for photosynthesis and must therefore live as parasites or saprobes. Most saprophytes are dependent on the food energy they absorb from decaying tissues which they help break up. They generally release digestive enzymes onto a food source, partially dissolving it to make the necessary organic or inorganic nutrients available (Roberts 2011).

4.2.5 Bacteria

Bacteria are microscopic unicellular prokaryotic organisms characterized by the lack of a membrane-bound nucleus and membrane-bound organelles. Most bacteria are of one of three typical shapes—rod-shaped, round, or spiral. Some bacteria (those known as aerobic forms) can function metabolically only in the presence of free or atmospheric oxygen; others (anaerobic bacteria) cannot grow in the presence of free oxygen but obtain oxygen from compounds. Most bacteria are heterotrophic, living off other organisms. Most of these are saprobes, bacteria that live off dead organic matter (Singleton 1992). Carbon may be obtained from both organic compounds and by fixing carbon dioxide. Many bacteria are **chemolithoautotrophs** who obtain energy from the oxidation of inorganic compounds and carbon from the fixation of carbon dioxide. Examples: nitrifying bacteria, sulphur-oxidizing bacteria, iron-oxidizing bacteria.

4.3 Methods

After the sampling of sites, samples were kept in sealed plastic bags until prepared for the further study. Research methods like light microscopy, scanning electron microscopy, EDX and XRD were used. For electron microscopy, samples were attached with double sided adhesive tape to the stubs, coated with a thin layer of Au/Pd to generated the necessary electrical conductivity for studying at an accelerating voltage of 15 kV (ZEISS EVO MA15). For light microscopy, tape lift samples were coloured with specific stains to reveal the microorganisms' cell walls (NIKON MicrophotFX). For XRD, stone or salt samples were ground up and studied with a Bruker AXD 5005 XRD spectrometer. Water soluble salts were separated prior to the analysis.

4.4 Results and Discussion

Resident bacteria, fungi, algae, and lichens all play a part in weathering. The metabolisms of these microorganisms generate oxalic acid which reacts with calcite and leads to the formation of calcium oxalate. Such reactions might even occur 2–3 cm beneath the stone surface.

Under appropriately humid conditions, fungi can live not only on a stone's surface but also within its pores, and the organic acids they produce can destroy such generally susceptible rocks as limestone, dolomite, and sandstone. The destructive influence of fungi can also lead to changes in the degree of oxidization of certain ions, causing changes in colouration or even flaking.

In humid climates, a major role in physical destruction and the appearance of secondary stone discolourations can be played by algae colonies which keep the underlying stone surfaces moist. In cooler climates, the characteristic reddish-brown crust that appears on objects made of limestone and marble is the work of lichens. Bacteria are another group of microorganisms that operate actively on rocks. This is particularly true for autotrophic bacteria, which obtain the energy they need to live by catalysing certain chemical reactions in their environment. Such organisms include sulphofobacteria, able to quickly deteriorate stonework in the presence of sulphuric acid, and nitrobacteria which oxidize non-organic nitrogen compounds (Mansch et al 1998).

Certain strains of heterotrophic bacteria are also able to survive in stone, even with the very small amounts of organic compounds available. Such bacteria usually give rise to pink, orange, or red spots or brownish "water stains," especially on sculptures and architectural elements.

In this survey, 7 medieval churches in Saaremaa and 1 in the mainland were studied (Table 4.1.

Table 4.1 The list of churches and types of detected microorganisms causing biodeterioration

Church	Algae	(Un)Visible Surface Mould	Wood rot	Pink coloration (bacteria)	Insects
St Peter's and St Paul's Church in Kaarma	x		x		
St Catherine's Church in Karja	x			x	
St Michael's Church in Kihelkonna	x	x	x	x	
St Catherine's Church in Muhu	x			x	
St Martin's Church in Valjala	x		x		
St James' Church in Püha	x	x			x
St Mary's Church in Pöide	x	(x)	x	x	
Church of the Holy Cross in Risti	x	(x)		x	

The evidence of biodeterioration was detected by visual inspection (algae, wood rot, insect damage); mould deterioration was determined by visual and light microscopy investigation and pink colouration was detected as bacterial attack by scanning electron microscopy.

4.4.1 Algae and salts

The primary inorganic nutrients for algae are P, N, and C. Hydrogen (H) and oxygen (O), found in water (H_2O) are also essential for algal growth. Other micronutrients required for growth and enzymatic activity include calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe), manganese (Mn), sulphur (S), zinc (Zn), copper (Cu), and cobalt (Co). Commonly, majority of these elements are provided by contaminated air or salts precipitated on the surface of the stone walls. In Saaremaa air contamination is minor and majority of salts come from thick moist stone walls. From the necessary chemical elements listed above, Ca, K, Mg, Na, and Zn are present at all researched sites (Table 4.2).

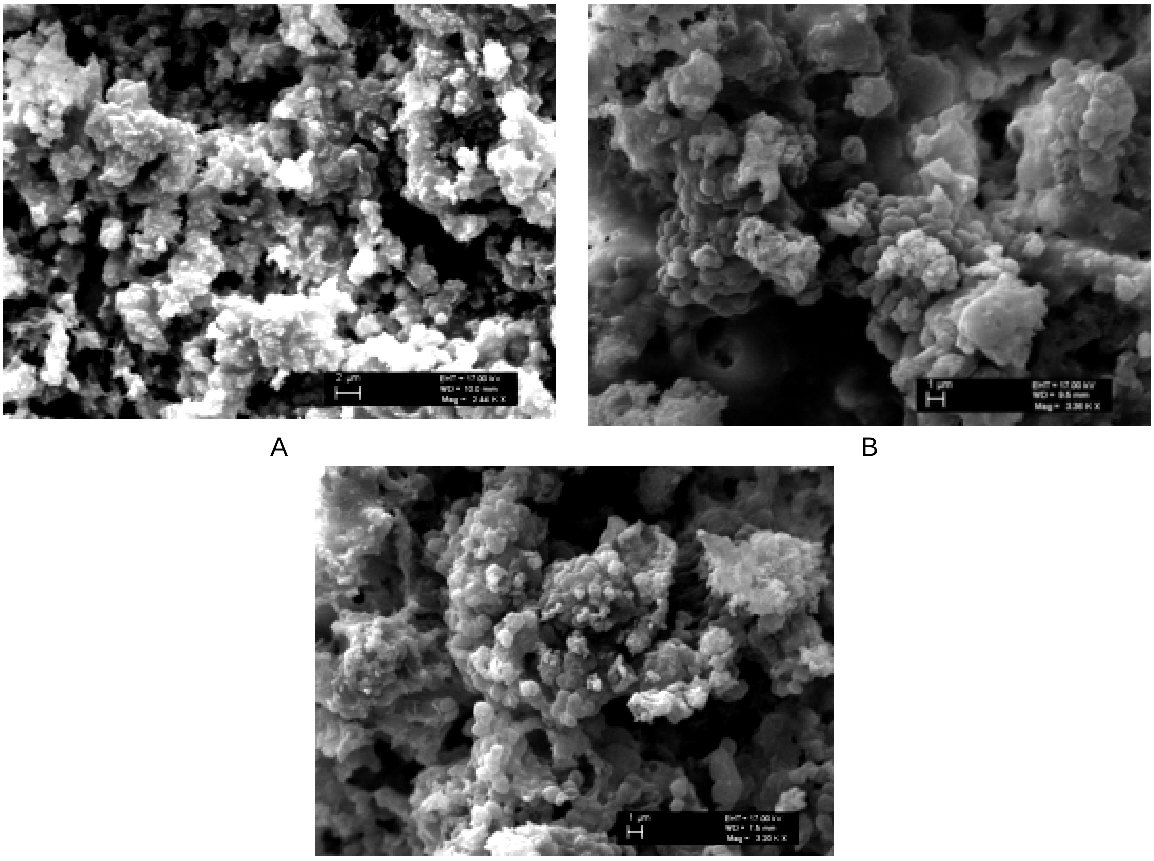
Table 4.2 Locations of salts.

Formula	Name	Site			
KNO3	Nitre; syn	Kaarma	Kihelkonna	Püha	Valjala
CaCO3	Calcite; syn	Kaarma	Kihelkonna	Püha	Valjala
CaCO3	Calcite; syn	Kaarma	Kihelkonna	Püha	Valjala
SiO2	Quartz	Kaarma	Kihelkonna	Püha	Valjala
MgCa(CO3)2	Dolomite	Kaarma	Kihelkonna	Püha	Valjala
NaCl	Halite; syn	Kaarma	Kihelkonna	Püha	
ZnO	Zincite; syn		Kihelkonna		
K4O(NO2)2	Potassium Oxide Nitrite		Kihelkonna		
Na2CO3·H2O	Thermonatrite; syn		Kihelkonna	Püha	
Na3H(CO3)2·2H2O	Trona		Kihelkonna	Püha	
Na2(CO3)(H2O)7	Sodium Carbonate Hydrate			Püha	
K2(SO4)	Arcanite; syn				Valjala

None of these salts are biocides. Naturally, the benefit or disadvantage of the salt occurrence depends on the concentration. Generally, this is only a problem in water ponds, not on the surface of stone walls (Tamburic et al, 2012). Dispersed precipitation of salts may affect the growth of algae only locally. Thus, salt precipitations were a factor facilitating the growth of algae.

4.4.2 Investigation of discoloration of plaster and stone surfaces

Discoloured plaster surfaces may contain both mould and bacteria. The specific strains are difficult to distinguish and require special laboratory investigation. Most discolouring organisms in plaster or stone surface layer are not identified (Gaylarde et al, 2003). In this study, only the occurrence of discolouring mould and bacteria were detected by scanning electron microscopy.

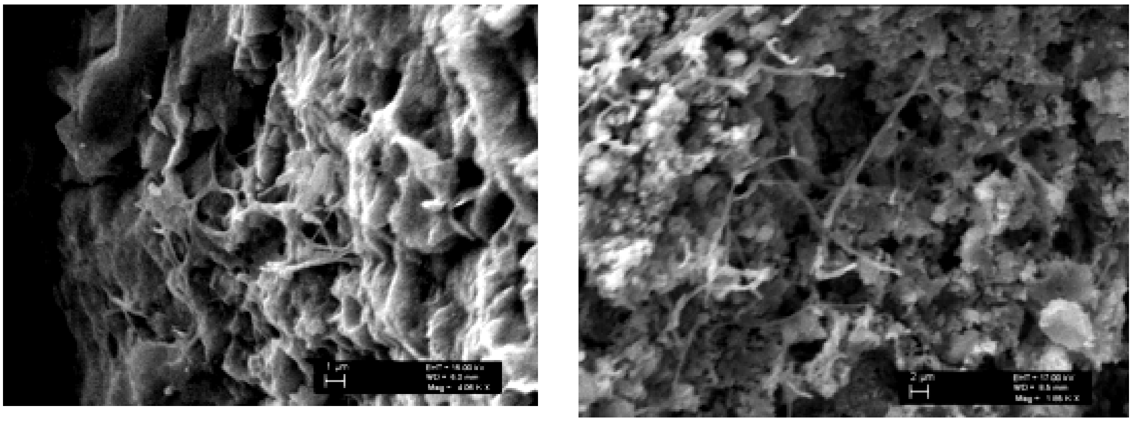


A B

C

Figure 4.1 Evidence of colonies of round-shape bacteria on the surface and inside the plaster: A: Muhu B: Karja C: Kihelkonna

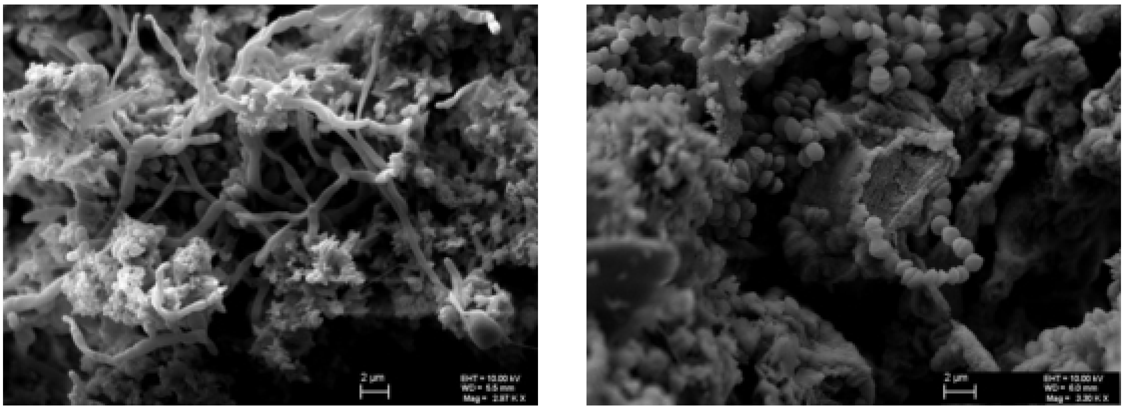
In Karja, Kihelkonna and Muhu Churches, colonies of round-shape bacteria on the surface and inside the pink-coloured plaster were detected (Figure 4.1). There was no evidence of corrosive influence due to the metabolic products of microorganisms.



A B

Figure 4.2 Contamination of the surface of plaster with fungal mycelium A: Risti B: Pöide

In Risti and Pöide Churches, the discoloured plaster surface layer was colonised by mould (Figure 4.2). No bacteria were detected.



A B

Figure 4.3 Different types of fungal and bacterial colonies inside the top painting at the Church of the Holy Cross in Risti. A: Fungal mycelium B: Bacterial threads

In Risti Church, different types of fungal mycelium and bacterial threads were detected where the plaster was painted with many layers of different paints (Figure 4.3 A, B). The growth of bacteria was probably facilitated by nutrients from the paint layers.

4.4.3 Biodeterioration in St Peter's and St Paul's Church in Kaarma

A: Algal growth on the walls B: Algal growth and salts C: Rot damage of the floor boards near the walls

Figure 4.4 Algae and wood rot are the main types of biodeterioration.

In Kaarma Church, an interesting phenomenon occurred where algae grow near a source of salt precipitation (KNO_3) (Figure 4.4 B). Algal growth is widely spread over the walls (Figure 4.4 A, C). So far, no pink-coloured areas were found.

4.4.4 St Catherine's Church in Karja

A: Salts deposition and algal growth B: Algal growth on the surface of post foundation C: Algal growth and pink coloration on the walls

Figure 4.5 Biodeterioration in St Catherine's Church in Karja. In Karja Church, algal growth and plaster discoloration resulting from pink bacteria occurred in large areas.

4.4.5 St Michael's Church in Kihelkonna

A: Pink colouration in the side door gallery B:Choir wall damaged by mould C:Algal growth on the plaster

Figure 4.6 Biodeterioration in St Michael's Church in Kihelkonna

In Kihelkonna Church, pink colouration of plaster (Figure 4.6A) in the gallery of the side door is rapidly developing. This is caused by bacteria. Mould damage also appeared on the wall of the choir cleaned in the process of restoration shortly after the work was concluded. Airborne mould *Cladosporium sp.* (Figure 4.6 B) was detected. Algal growth was detected particularly on the plaster layer (Figure 4.6 C), and very rarely on the stone wall.

4.4.6 St Catherine's Church in Muhu

p

A: algal growth near the floor B: discoloration on walls C: discoloration on walls

Figure 4.7 Biodeterioration in St Catherine's Church in Muhu.

In Muhu Church, large areas of plaster discolouration were detected that were caused by bacteria (Figure 4.7 B, C). The areas of algal growth were mainly found near the floor level (Figure 4.7 A).

4.4.7 St Martin's Church in Valjala

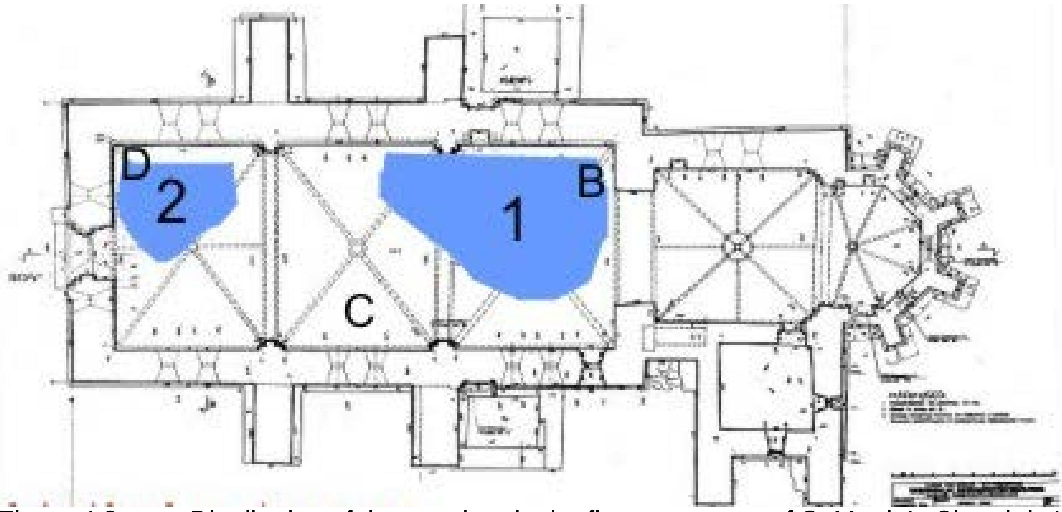


Figure 4.8 Distribution of the wood rot in the floor structures of St Martin's Church in Valjala

A Top view of the floor

B Site B (Figure 4.8)

C Site C (Figure 4.8)

D Site D (Figure 4.8)

Figure 4.9 Biodegradation in the floor structures

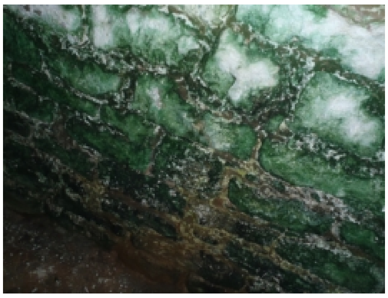


Figure 4.10 Biodeterioration in St Martin's Church in Valjala

Wide-scale algal growth is facilitated by the high indoor moisture content spread on the internal walls. Even though from the outside, the floor looks fine (Figure 4.9), the main problem in this church is widely spread wood rot under the floor (Figure 4.8). The area is marked in blue. In site D, the fruiting body of *Coniophora sp.* was discovered. In favourable conditions, this fungus can quickly destroy the whole floor. Eradication of wood rot should be stared as soon as possible.

4.4.8 St James' Church in Püha

A: Yellowing of the Linseed primer

B: Algal deterioration on the loft level and higher

C: Anobium damage of the bench on the loft

Figure 4.11 Biodeterioration in St James' Church in Püha.

In Püha Church, a large area of algal deterioration was detected on the ground and loft levels (Figure 4.11B). In the entrance hall, linseed primer was found to be yellow and deteriorated by mould. In the loft, Anobium damage was detected on one bench. There was no sign of it spreading to other benches.

4.4.9 St Mary's Church in Pöide

A: Inside B: Northern side, 2012 C: Northern side, 2013

Figure 4.12 Biodeterioration in St Mary's Church in Pöide.

Algae have spread widely both inside and outside the Pöide Church. The area of development of the algae inside (Figure 4.12 A) has not changed over the project period. Outside, on the northern side of the church (Figure 4.12 B), a temporary roof was built over the excavated area for archaeological excavations. That caused massive growth of algae on all stone surfaces under the roof. Over the project period, some reduction of the outside algae growth occurred (Figure 4.12 C).

4.4.10 Church of the Holy Cross in Risti

Besides algal growth, there was an interesting occurrence of threaded pink bacteria and mould (Figure 4.3) on painted plaster surfaces. The plaster was painted with at least 5 layers of paint Figure 4.13 A) with different physical properties and that caused it to crack and separate. In the fractured spots, an old layer of oil paint was revealed (Figure 4.13 B).

A: 5 layers of finishing materials B: The darker central layer is a paint containing linen primer

Figure 4.13 Plaster layers.

The detached layer of paint created favourable conditions beneath it to maintain stable moisture conditions for the mould and bacteria to grow in. Bacteria coloured the plaster surface pink but did not colonise the upper blue-coloured layers of paint.

Figure 4.14 Copper salt deposit on the outside wall

Outside, at the front facade of the church, a bluish green copper salt deposit had formed due to rainwater flowing over the copper metal sheet roof.

4.5 Conclusions

Algal growth and pink colouration due to specific bacteria occurred massively in the studied medieval churches. It seems that algal growth is stable but areas with pink colouration are getting larger. Mould growth is mainly visible only where organic substances are available (linseed primer, paints). Nevertheless, mould is spread more widely if looking the inside plaster and between the paint layers under a microscope. Therefore, it should also be considered a problem.

Wood rot is a severe problem in Valjala Church and the infected floor area is constantly growing. Measures to stop the rot should be taken as soon as possible. The rot has been identified as brow wet rot *Coniophora sp.* In other churches, the floor near the walls is damaged by unidentified wet rots but the stable indoor moisture conditions keep its growth slow.

Insect damage was minor, occurring only in only in one site (Püha Church). Wood borer degradation was detected in benches in the loft.

How hospitable stone surfaces are for all sorts of microorganisms depends on the porosity of the stone, absorbability, and mineral composition. The fight against such organisms is made even more difficult by the fact that the internal breakdown of a stone for other reasons can already be at an advanced stage before any sort of alarming changes occur on the surface. Moreover, some microorganisms can even withstand extreme conditions such as subjecting the stone to drying for extended periods.

In order to protect stonework from the harmful impact of chemically active rain, a process called “hydrophobization” is used, involving agents that prevent moisture from being absorbed by stone. These agents usually also act as biocides, killing the microorganisms living in a stone. The applied solutions are chosen so as to easily impregnate the material, to combine well with its mineral components, and also not to change the structure of the stone, retaining its natural porosity and outward appearance. Coupled with increasingly more efficient methods for cleaning old monuments and building facades, such protective measures substantially prolong the lifespan of stone monuments.

According to an overview (Gaylarde, 2003), measures for the prevention of biodeterioration, including the use of biocides, require expending millions of euros per year. These costs do not include the research and development programmes underway throughout the world with the aim of developing resistant materials and more environmentally acceptable biocides.

A multidisciplinary approach is important when studying microbial impact on building materials. It is necessary to integrate different concepts in order to determine the mechanisms of deterioration as well as methods of control. Microbiologists, specialists in materials technology, chemists and geologists have to work together in order to avoid the use of protective treatments that can cause more damage to the building material than the microorganisms themselves (Gaylarde, 2003).

4.6 Acknowledgments

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5 A STUDY OF HISTORICAL PLASTER AND RENDER AND PRACTICAL TESTS OF CONTEMPORARY CONSERVATION TECHNIQUES AND MATERIALS

Kaire Tooming

5.1 Background

Plaster and its finishing layers suffer considerably from problems related to poor maintenance and the indoor climate of the churches. Moisture and high relative humidity cause numerous problems with wall and vault surfaces. Especially vulnerable are the murals. The variety of problems caused by moisture is broad, ranging from the soiling of the surfaces caused by the growth of micro-organisms to damage to the plaster and finishing layers caused by freezing cycles and salt crystallization during drying. The formation of crystals on painted surfaces is especially destructive as it causes surface damage such as flaking and paint loss.

The research objectives were:

- To study and map the condition of plaster/render and the finishing layers at one unheated Estonian church
- To test contemporary conservation methodologies and lime based conservation mortars in situ
- To test contemporary conservation mortars in laboratory

The expected outcomes were:

- Documentation for intended conservation works
- An evaluation of contemporary lime-based conservation mortars

An in situ study of plaster/render and finishing layers was carried out from May to September 2012 at Pöide Church. In situ tests of contemporary conservation methodologies and lime-based conservation mortars took place at the same time. The study and tests were carried out by the Rändmeister conservation firm, specialized in the study and conservation of historic interiors and facades. The study of wall and vault paintings was carried out in co-operation with the Department of Cultural Heritage and Conservation at the Estonian Academy of Arts. The laboratory study of historical plaster and render samples, as well as contemporary conservation mortars was conducted by the Tallinn University of Technology. The results of the laboratory studies are presented in a separate chapter of this report (see chapter 6, Laboratory study of plaster, render and mortar samples).

Pöide Church is situated in the Eastern part of Island Saaremaa, Estonia. It is a medieval parish church that formed a part of a stronghold of the Teutonic Order (now in ruins) in the Middle Ages. Since 1940, when it lost its roof and spire in a fire, the church has been almost neglected. The church was roofed again about 20 years later. Its state of conservation has long been very poor due to the leaking roof. In the 1990s, conservation works took place in the chancel. Other parts of the church have not been conserved. The restoration of the roof is ongoing.

5.2 Study of historical plaster/render

The aim of the field study was to document the current condition of the plaster/render and finishing layers. This information was needed for the preparation of documentation for the conservation of the interior and facades. The method used was the stratigraphic study of plaster/render and finishing layers. In addition to mapping the condition of the layers, building archaeological data was collected. The study area covered the northern and southern facades and the interior of the nave and the tower. As the chancel was conserved in the 1990s, the emphasis of the research was on other parts of the church.

A total of 12 different types of plaster/render were found on the walls and vaults of Pöide Church, dating from the 13th to 19th centuries. The study revealed that similar mortars were used for both plaster and render during a construction period. All types of plaster/render are different and easily distinguishable as the colour of the sand varies. All types contain local fine sea sand mixed with coarse sand and clay. The ratio of fine and coarse sand is different in different types of mortar. The amount of binding lime used in mortars varies as well.

The condition of plaster and render at Pöide Church is poor. Damage found include: detached layers, loose and damaged surfaces, hardened surfaces. All these types of damage can appear simultaneously. Damages are mostly related to excessive moisture. The condition of the church worsened dramatically when it stood without a roof for almost 20 years. Its condition has not improved since then as there have been continuous leakage problems and the overall state of maintenance has been very poor. An additional source of moisture is found on the northern side of the church where a low and wide roof is covering a zone of archaeological excavations.

5.3 Study of wall and vault paintings

Wall and vault paintings were studied in the nave and the tower. A complementary study was carried out in the chancel to acquire more data on different paintings found during the conservation works in the 1990s. Excessive opening of paintings was avoided to prevent future damage to the recently opened paintings by frost and salt crystallization.

The study revealed that traces of gothic wall and vault paintings can still be found in the tower and the nave. The murals have been painted on a layer of wet or partly dried plaster, creating a fresco-like effect. The condition of the paintings and plaster under these varies from very poor to satisfactory. The paintings found from that period highlight architectural details such as vaults, arches and windows. The compositions used are geometrical with some floral detailing. In the chancel, the conservation works in the 1990s revealed some traces of gothic paintings. The study showed that the extent of preserved gothic murals on the walls and vault of the chancel is bigger than presumed. Together with preserved mural fragments from the nave and the tower, the paintings in the chancel form an elaborate composition of gothic wall and vault paintings.

In addition to medieval murals, fragments of later paintings were found from the nave. The fragments opened were small and the study of these will continue during future conservation works. In the chancel, the condition of the paintings opened in the 1990s was monitored.

5.4 Field tests of contemporary conservation techniques and materials

The tests were carried out to find solutions for cleaning surfaces from damaged plaster/render and finishing layers. At the same time, tests of lime based conservation mortars were carried out on the eastern facade. Continuous inspection of the test patches over the next couple of years will provide the conservators information on suitable mortar types. A test patch for finishing and consolidation of plaster layers with damaged surfaces was prepared to test the sustainability of the chosen method.

The field study provided conservators and conservation architects with data required for the preparation of conservation documentation for Pöide Church (see Appendix 1). The documentation provides conservation solutions for the facades and the interior, including portals and other openings.

5.5 Workshop and training for conservation students

In addition to the field studies, a workshop and training for conservation students from the Estonian Academy of Arts and Gotland University took place at Pöide Church 13–24 August 2012. The students had the chance to have a hands-on experience of studying a medieval church. During the workshop on plaster/render conservation and building archaeology, the students practiced their skills on archaeological research and mapped the state of conservation of plaster and finish. They also had seminars on several research and conservation subjects related to medieval churches.

6 LABORATORY STUDY OF PLASTER, RENDER AND MORTAR SAMPLES

Lembi-Merike Raado, Tiina Hain

6.1 Introduction

The objective of this study was to examine the influence of the composition of lime mortars on their structural and durability characteristics.

An experimental study of lime mortars was carried out using dry hydrated lime and six different aggregates. Lime has been used as a binder in architectural heritage mortars since ancient times.

The experimental study was designed using existing standards and specific procedures that have been used in the laboratory for mortar preparation, curing conditions and test specifications. The characteristics were selected that are needed for protecting the walls where the mortar has been used and to prevent the degradation of the mortar by increasing its durability.

To compare the compositions of contemporary mortars with ancient plasters, samples of plaster from Pöide Church in Saaremaa, Estonia were analysed.

The report presents the test materials used for the elaboration of the compositions, the compositions of lime mortars, results, and finally conclusions.

6.2 Methods

6.3 Experiments

The experimental study was designed using the following standards:

- Lime was tested according to the standard EVS-EN 459-2;
- Compressive strength was determined in accordance with EVS-EN 196-1, except for water content that was chosen so as to achieve the required consistency.
- Chemical composition was determined according to EVS-EN 459-2 and EVS-EN 196-2.
- Characteristics of aggregates were assessed by:
  - particle size distribution: EVS-EN 933-1,
  - fineness modulus: EVS-EN 13139,
  - bulk density: EVS-EN 1097-3,
  - humus content of aggregates: EVS-EN 1744-1;
- Frost resistance of mortars was determined according to the GOST 5802 method.

The demoulded specimens were stored continuously at a temperature of (20 ± 1) °C and a relative humidity of at least 60%. Lime paste of standard consistency has a specified resistance to penetration by a standard plunger. The water content required for such a paste was determined by trial penetrations of pastes with different water contents. Penetration values were measured with a plunger apparatus. Extraction with hydrochloric acid was used to dissolve building lime in order to determine calcium oxide and magnesium oxide content. CO_2 contained in the building lime in the form of carbonates was extracted by reaction with hydrochloric acid and determined volumetrically.

6.4 Source materials used for elaboration of the compositions

Dry hydrated lime

Bulk density of the dry hydrated lime (produced in Saaremaa in 2012) was 510 kg/m^3. The chemical composition of the dry hydrated lime was tested in our laboratory as source material and the results are presented in Table 6.1:

Table 6.1 Chemical composition of the used lime

Insoluble residue, %	SO3, %	CaO, %	MgO, %	Loss on ignition, % 525 ºC	Loss on ignition, % 975 ºC	CO2, %
0.10	0.46	54.30	15.78	15.45	19.85	4.40

Aggregates

Particle size distribution and the type of aggregates play an important role from the point of view of the density, water vapour permeability and strength parameters of the mortars. The selection of aggregates is directly affected by the purpose the mortar is used for; hence, filling and finishing mortars differ by maximum grain size and particle size distribution. On the other hand, the packing density of grains as a skeleton in the hardened mortar has an effect on the quantity of binder and water in mortar and therefore also on the strength, water absorption and other durability parameters. Consequently, besides the parameters of used lime binder, the particle size distribution of sand, sand mixes and other aggregates such as chamotte in plasters are of considerable importance.

As a result of a sieving analysis, fineness modulus (FM) can be calculated and is specified as:

- Coarse graded (CF) FM=3.6–2.4,
- Medium graded (MF) FM=2.8–1.5
- Fine graded (FF) FM=2.1–0.6 aggregates

In addition to grain grading, the content of fines, dust, clay and organic materials also influence the hardening process. Percentage passing the 0.063 mm sieve should be < 3% by mass.

Two sands were used for preparing lime mortars in laboratory: fine sand and "silicate" sand with a grain size of 0.063…2.0 mm. Some sand was also replaced with finely ground firesand (chamotte) both in filling and in finishing mortars. The grades of used aggregates are presented in Table 6.2.

Table 6.2 Particle size distribution of aggregates – retained material on the sieve and cumulative remaining material

Sieve aperture, mm	Fine sand (SF)		Coarse sand (SIL)		Mixed aggregate for coarse mortar (aggr.ST)		Mixed aggregate for finishing mortar – sieved sand and chamotte (cham.V)		Component for aggregate (chamotte) for coarse mortar (cham.ST)		Component for aggregate (chamotte) for finishing mortar) (aggr.V)	
	Ret. mat	Cum. rem.	Ret. mat	Cum. rem.	Ret. mat	Cum rem.	Ret. mat.	Cum. rem.	Ret. mat.	Cum. rem.	Ret. mat.	Cum. rem.
	%		%		%		%		%		%	
8	0.0	0.0	0.0	0.0	0.0	0.0	8	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	1.4	1.4	4	0.0	0.0	0.0	0.0	1.4
2	0.0	0.0	0.0	0.0	12.3	13.7	2	0.0	0.0	0.0	0.0	12.3
1	2.2	2.2	31.9	31.9	45.9	59.6	1	2.2	2.2	31.9	31.9	45.9
0.5	28.0	30.2	40.4	72.3	26.8	86.4	0.5	28.0	30.2	40.4	72.3	26.8
0.25	53.8	84.0	22.2	94.5	10.0	96.5	0.25	53.8	84.0	22.2	94.5	10.0
0.125	15.2	99.2	5.3	99.8	3.1	99.5	0.125	15.2	99.2	5.3	99.8	3.1
0.063	0.6	99.8	0.2	100.0	0.4	99.9	0.063	0.6	99.8	0.2	100.0	0.4
< 0.063	0.2	100.0	0.0	100.0	0.1	100	< 0.063	0.2	100.0	0.0	100.0	0.1
FM	2.16		2.99		3.57		2.15		4.23		2.72	
Density, kg/m^3	1490		1580		1350		1380		1000		1240	
Humus	satisfactory		satisfactory		satisfactory		satisfactory		satisfactory		satisfactory	

From the test results, it is clear that despite "silicate" (SIL) and fine sand having an identical fraction size of 0.063–2 mm, their fineness modulus is different (FM of 2.99 and 2.16 respectively). The addition of chamotte enhances the fineness modulus of aggregate.

6.5 Results and discussion

6.5.1 Analysis of plaster from Pöide church

The chemical composition (EVS-EN 459-2), quantity of aggregate and particle size distribution (EVS-EN 933-1) were determined. Samples were ground and dried at (110 ± 5) °C. Chemical composition according to EVS-EN 196-2 is given about dry sample.

Table 6.3 Chemical composition of ancient plaster from Pöide church.

Sample	Insoluble residue, %	Loss on ignition % 525 °C	975 °C	CO_2, %	$CaCO_3$, %
Plaster of Pöide church	55.0	12.2	19.9	7.7	17.6

Lime mortars continue to harden for an entire year by carbonization. Therefore, it is impossible to determine the amount of found calcium carbonate. The detected amount of 17.6% does not preclude the possibility that particles of limestone can be found in the plaster that have not decomposed during the combustion process.

The calculation presumes that when treating the mortar with a 5% HCl solution, the quartz sand forms the insoluble part and the soluble portion is the binder. Binder is calculated as a dry substance. The results indicate that the ratio of lime binder with additives (no decomposed limestone, clay etc.) to aggregates in ancient Pöide plaster was 1:2.2.

The impact of the aggregate particle size distribution properties of mortar was described by Konow (2003) and Thomson (1999). Table 6.4 presents the results of the particle size distribution of ancient Pöide mortar.

Table 6.4 Particle size distribution of sand separated from plaster by dissolution by EVS-EN 933-1 (anc. mortar)

Sieve aperture size, mm	Retained material, %	Cumulative material remaining, %	Cumulative material passed, %
4	0.0	0.0	100
2	1.7	1.7	98.3
1	3.0	4.7	95.3
0.5	7.1	11.8	88.2
0.25	14.1	25.9	74.1
0.125	32.9	58.8	41.2
0.063	32.3	91.0	9.0
< 0.063	9.0	100.0	0.0

Fineness modulus FM = 1.03.

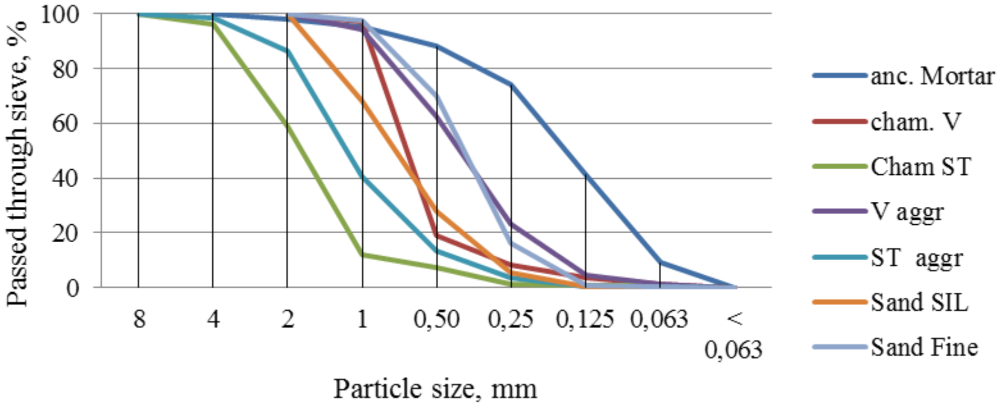

Figure 6.1 The comparative curves of sieve analysis of used aggregates.

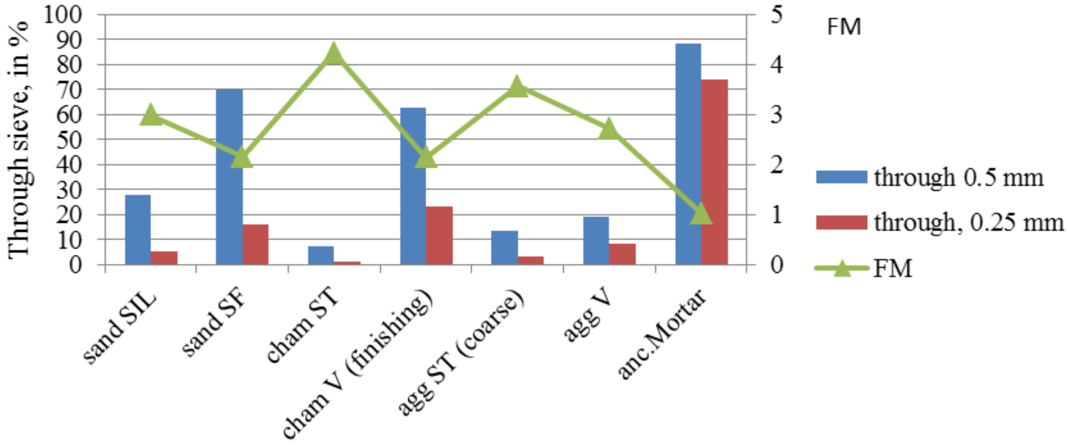

Figure 6.2 Tested aggregate material passed through 0.5 and 0.25 sieves. Fineness modulus of aggregates or their mixes

From the data in Table 6.1 and Table 6.2, it follows that the aggregate used in ancient plaster is significantly finer compared to the contemporary aggregates or their mixes. Especially remarkable is the low fineness modulus which is much greater in modern mixes. It is certainly not possible to state on the ground of this result that aggregates with low fineness modulus and relatively homogeneous grain size were used in all plasters and mortars regardless of their purpose.

6.5.2 Compositions of lime mortars

As for different assignments, test specimens with various shapes were needed. The test was implemented in two stages. Variable mixes were thus also examined in various stages to expand upon the optimization possibilities of compositions. The amounts of water used were designed so that all mortars would have comparable consistencies using the flow table test.

In the first stage, the water demand, flexural and compressive strength of laboratory-made mixes of 1:3; 1:2 and 1:1 lime: sand/chamotte (Table 6.5) were determined. These results were compared with the results of rendering-filling mortar EM $(ST)_{1:2}$ and finishing mortar EM $(V)_{1:2}$ used in practical conservation works.

Table 6.5 Compositions of lime mortars.

Designation	Lime/sand	Aggregate type	Water: binder
$LSIL_{1:3}$	1:3	Coarse sand	0.72
$LSIL_{1:1}$	1:1	Coarse sand	0.60
$LSIL_{1:2}$	1:2	Coarse sand	0.60
$LSF_{1:3}$	1:3	Fine sand	0.67
$LSF_{1:2}$	1:2	Fine sand	0.64
$LSF_{1:1}$	1:1	Fine sand	0.60
$EM(ST)_{1:2}$	1:2	EM aggregate for coarse (ST) mortar	0.72
$EM(V)_{1:2}$	1:2	EM aggregate for finishing (V) mortar	0.64
$LFCh_{1:2}$	1:2	Fine chamotte	0.80
$LCCh_{1:2}$	1:2	Coarse chamotte	0.83

In the second stage, on the basis of the results of the previous tests, the compositions of mixes were chosen and specimens (Table 6.6) were made. Capillary water absorption, water vapour permeability, adhesion strength, frost resistance were tested, as well as compressive strength before the beginning of the frost resistance test. The results were compared when possible with the results of ancient plaster (anc. mortar) testing.

Table 6.6 Composition of mortars and characteristic parameters.

Designation	Lime: aggr. ratio	Aggregate	Water/ lime ratio	Penetration depth, cm	Flow diameter, mm	Mortar-cone, cm	Air content, %	Density, kg/m^3
$SF_{1:3}$	1:3	Fine sand	0.85	4	150	2.2	4.3	1995
$SIL_{1:3}$	1:3	Coarse sand	0.75	4	142	2.2	3.4	2070
$(FCh+SF)_{1:3}$	1:3	Fine chamotte + fine sand	0.96	5	153	2.4	3.8	1945
$(CCh+SIL)_{1:3}$	1:3	Coarse chamotte + coarse sand	0.86	3	116	2.0	3.9	1953
$(FCh+SF)_{1:2}$	1:2	Fine chamotte + fine sand	0.78	4	163	2.8	3.1	1905
$(CCh+SIL)_{1:2}$	1:2	Coarse chamotte + coarse sand	0.80	4	172	2.4	3.1	1884

The results in Table 6.6 reveal that the increase of the ratio of aggregate in the mix causes the increase of density, the addition of finely ground chamotte decreases the density of mortar, the application of coarse sand and ground chamotte decreases the density of the mix.

From the data in Table 6.6, it is clear that when using fine aggregate, the amount of water required for the mix for the same workability increases compared to (FCh+SF) and (CCh+SIL), the more the larger is the aggregate content of the mix compared to (FCh+SF) and (CCh+SIL) mixes 1:2 and 1:3. The addition of finely ground chamotte increases the water demand of the mix.

6.5.3 Compressive and flexural strength of lime mortars

Mortars were prepared in a Hobart mixer. For determining the compressive strength, the pieces of the prisms remaining after the flexural strength test were used. Three specimens (40 × 40 × 160 mm) were tested at the age of 7 and 28 days in order to find the average value of flexural strength; next, the six pieces were tested in compression. The strength development of mortar compositions with different lime/aggregate ratio and aggregates are given in Figure 6.3.

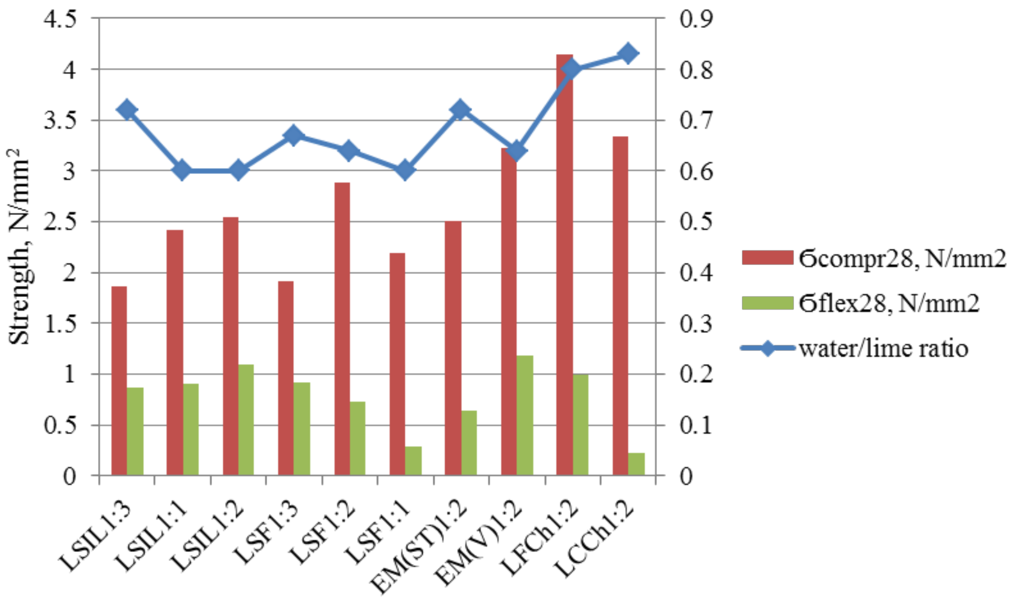

Figure 6.3 Flexural and compressive strength of lime mortars after 28 days of hardening and the water demand of mortars as water/ lime ratio. Mortars were hardened at + (20 ± 2) ºC and relative humidity of (95 ± 5)%

Figure 6.3 shows that:

- Mortars made with SIL sand a have highest flexural and compressive strength when the mix ratio is 1:2; in case of 1:3, these values are much lower which can also be seen in the increase of water demand.
- Lower values were measured for mixtures with coarse aggregate. However, after a longer period, the strength of the compositions with coarse aggregate increased and was similar to

those containing fine sand. This means that the inclusion of coarse aggregates is advantageous for long term strength.

- Water demand of mortars made using fine sand SF is generally higher than mortars made with coarse SIL sand. At the same time, compressive strength is the highest for a 1:2 mix; flexural strength is to certain extent higher in the case of 1:3 mix and is reduced corresponding to the increase of aggregate content.
- Finishing mortar mix $EMV_{1:2}$ and filling mortar mix $EMST_{1:2}$ blended by the restorer had relatively high strength. Finishing mortar mix $EMV_{1:2}$ had a compressive strength of up to 3, 2 N/mm^2. Filling mortar mix $EMST_{1:2}$ had a higher water demand and lower strength.
- The highest compressive strength was achieved using finely ground chamotte as an aggregate in a 1:2 mix (lime: finely ground chamotte) despite the relatively high water demand of the mix. At the same time, flexural strength remained equal to sand mixes. Using coarse chamotte in the mix reduced its flexural strength considerably.

6.5.4 Adhesion strength

Mixes are marked with indexes 1:2 or 1:3 indicating the ratios of lime binder and aggregate by weight. Figure 6.4 shows that the adhesion strength of mortars made using fine sand exceeds the adhesion strength of mortars made using coarse sand; increase of the ratio of lime binder improves adhesion strength. The content of fine finely ground chamotte decreases the adhesion strength of mortar made with fine sand. On the other hand, coarsely ground chamotte with coarse sand in lime-rich mix enables achieving superior adhesion strength and results in adhesion strength analogous to pure quartz sand.

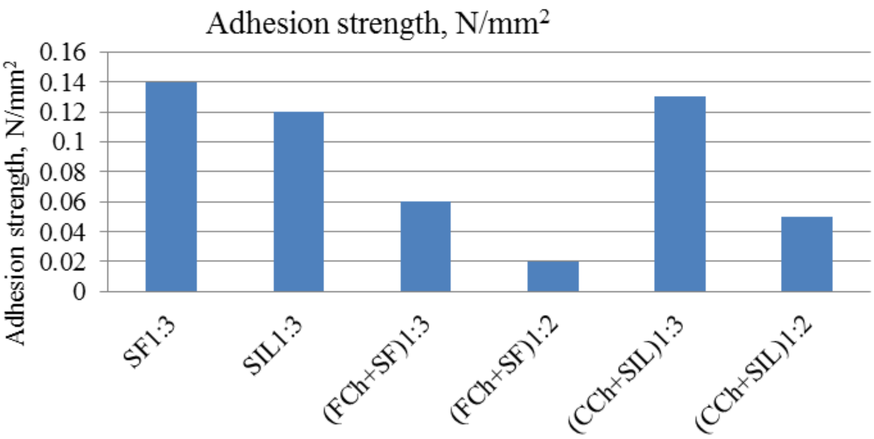

Figure 6.4 Adhesion strength of lime mortars depending on the type and quantity of the aggregate in the mortar

For the analysis of mechanical resistances, it should be kept in mind that if the mortar is expected to be durable, it should have enough mechanical resistance to withstand the stresses it will face. This means that the compressive, flexural and adhesion strengths should not be too low. From this point of view, the better performance of mortars made with fine sand and finely ground chamotte as an aggregate in mix 1:2 should be emphasized.

6.5.5 Water vapour permeability

For determining water vapour permeability, the mortar specimens were made on frames sealed against water vapour and hardened for 28 days at + (20±1) ºC and relative humidity (50±5)%.

After 28 days of hardening, the specimens were sealed hermetically with a silicone sealant on the testing container so that the space between the KNO_3 water solution and the test specimen was (10 ± 5) mm.

Water vapour transmission area was calculated as the mean of upper and lower areas. Test assemblies were weighed at regular intervals to determine the quantity of vaporised water. Air temperature, humidity and pressure were recorded. Weighing was continued until five successive measurements of change in mass per unit time for each test specimen were constant within ± 5% of the mean value for that test specimen. Test results are presented in Figure 6.5, Table 6.7, and Table 6.8.

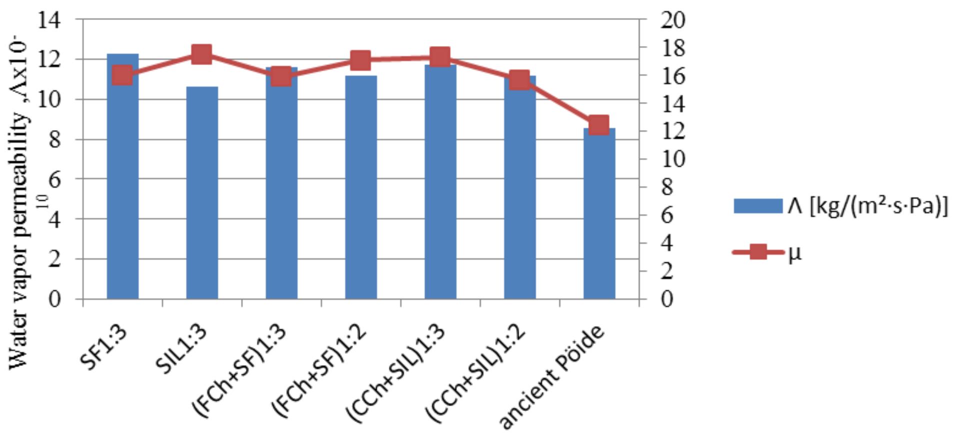

Figure 6.5 Water vapour permeability Λ (kg/ (m²·s·Pa)) of mortars with various compositions and water vapour diffusion coefficient μ

Table 6.7 Water vapour diffusion, permeability and diffusion resistance factor of the tested mortars

Designation	Thickness d, m	Area A, m^2	Water vapour diffusion Λ, kg/(m²·s·Pa)		Water vapour permeability δ, kg/(m·s·Pa)		Water vapour diffusion resistance factor, μ	
			single	average	single	average	single	average
SF1:3	0.0104	0.0185	$1.19\cdot10^{-09}$	$1.23\cdot10^{-09}$	$1.24\cdot10^{-11}$	$1.24\cdot10^{-11}$	15.9	16.0
	0.0097	0.0185	$1.26\cdot10^{-09}$		$1.23\cdot10^{-11}$		16.0	
SIL1:3	0.0103	0.0186	$1.11\cdot10^{-09}$	$1.06\cdot10^{-09}$	$1.14\cdot10^{-11}$	$1.12\cdot10^{-11}$	17.1	17.5
	0.0108	0.0186	$1.01\cdot10^{-09}$		$1.09\cdot10^{-11}$		17.9	
(FCh+SF)1:3	0.0108	0.0186	$1.17\cdot10^{-09}$	$1.16\cdot10^{-09}$	$1.26\cdot10^{-11}$	$1.24\cdot10^{-11}$	15.5	15.9
	0.0107	0.0186	$1.14\cdot10^{-09}$		$1.22\cdot10^{-11}$		16.2	
(CCh+SIL)1:3	0.0100	0.0187	$1.14\cdot10^{-09}$	$1.17\cdot10^{-09}$	$1.14\cdot10^{-11}$	$1.14\cdot10^{-11}$	17.2	17.3
	0.0095	0.0187	$1.19\cdot10^{-09}$		$1.13\cdot10^{-11}$		17.4	
(FCh+SF)1:2	0.0102	0.0175	$1.13\cdot10^{-09}$	$1.03\cdot10^{-09}$	$1.15\cdot10^{-11}$	$1.15\cdot10^{-11}$	16.9	17.1
	0.0123	0.0175	$9.26\cdot10^{-10}$		$1.14\cdot10^{-11}$		17.2	
(CCh+SIL)1:2	0.0109	0.0163	$1.18\cdot10^{-09}$	$1.12\cdot10^{-09}$	$1.29\cdot10^{-11}$	$1.25\cdot10^{-11}$	15.2	15.7
	0.0114	0.0163	$1.06\cdot10^{-09}$		$1.21\cdot10^{-11}$		16.2	
Ancient mortar from Pöide church	0.0185	0.0039		$8.53\cdot10^{-10}$		$1.58\cdot10^{-11}$		12.4

Table 6.8 Water absorption of mortars

Designation	Density, 28 days hardened, kg/m^3	Water absorption after 24 h water storage, %
$SF_{1:3}$	1738	14.0
$SIL_{1:3}$	1833	12.6
$(FCh+SF)_{1:3}$	1642	16.7
$(CCh+SIL)_{1:3}$	1697	14.6
$(FCh+SF)_{1:2}$	1614	17.7
$(CCh+SIL)_{1:2}$	1589	18.3

For testing the water vapour permeability of the ancient plaster from Pöide church, specimens with a diameter of 72 mm and thickness of 18.5 mm were cut from a plaster segment. Water vapour diffusion area A = 0.0039 m² was calculated as the mean of upper and lower surface. The testing procedure was similar to water vapour determination of laboratory made lime mortars. Test results are presented in Table 6.7 and Figure 6.5. Water vapour diffusion of mortars was relatively similar, within μ=15.7…17.5.

The impact of the aggregate particle size distribution on properties of mortar was also described by Konow (2003) and Thomson (1999). Our particle size distribution results presented in Table 6.4 agree with Konow (2003) and Thomson (1999).

Ancient mortar differed by water vapour diffusion resistance factor which was μ=12.4. The lowest water vapour diffusion was obviously caused by carbonation. Higher values of water vapour diffusion resistance factor μ are characteristic of mixes containing finely ground chamotte compared to only sand based mixes. From the results, it is clear that depending on the grinding level of finely ground chamotte and granulometry of sand, mixes with good packing efficiency and hence higher density can be made. A comparison of the results in Table 6.7 and Table 6.8 show that the mix $SIL_{1:3}$ with highest density has relatively low water vapour permeability, high water vapour diffusion resistance factor μ=17.5 and also low capillary water absorption.

6.5.6 Frost resistance of mortars

Results of frost resistance tests depend on various methods used in different countries (Maurenbrecher et al. 2009, Smits et.al. 2008). Frost resistance of mortars was determined according to the GOST 5802 method. According to this method, mass loss is limited to up to 5% of the mass of test specimen and the loss of compressive strength is limited up to 25%.

The results in Table 6.9 show that the mortar with a composition of 1:3 (lime: sand SF + coarse ground chamotte) has the highest compressive strength. The compressive strength of the 1:2 (lime: sand SF + fine ground chamotte) mortar is almost as high. The results prove that aggregates that give higher packing density enable making mortars with better strength characteristics. If the content of lime in the mortar increases, finer aggregates should be used.

Table 6.9 Change of mass loss and compressive strength of lime mortars during frost resistance test

Designation	Compr. strength before freezing, N/mm²	Average change of mass and compressive strength of mortar cubes, %, after freezing-thawing cycles								Cycles
		5		6		7		8		
		mass	Rc	mass	Rc	mass	Rc	mass	Rc	
SF1:3	1.30	1,4	-24.1	1,7	-30.9	1,9	-	2.5	-	5
SIL1:3	1.47	1.3	-20,0	1.6	-24,6	2.1	-29,2	2.3	-	6
(FCh+SF)1:3	1.22	1.3	-10.2	1.5	-15.4	1.6	-20.4	2.1	-27,7	7
(CCh+SIL)1:3	1.75	1,3	-16.2	1,6	-21.4	1,9	-24.1	2.1	-39.0	7
(FCh+SF)1:2	1.66	1.1	-7,8	1.4	-15,1	1.6	-17,6	1.8	-30,1	7
(CCh+SIL)1:2	1.43	2.1	-24.5	2,9	-30.5		-		-	5

Figure 6.6 and Figure 6.7 show that the freezing-thawing process provokes alterations in the structure: cracking and conversion of porosity which are reflected in the change of the mass of the material. Mass change and loss of strength begin already after a single freezing-thawing cycle. Mortar which is made with coarse sand and coarse chamotte and high lime content has the lowest frost resistance, evidenced by both the reduction in the mortar's strength and fast mass change.

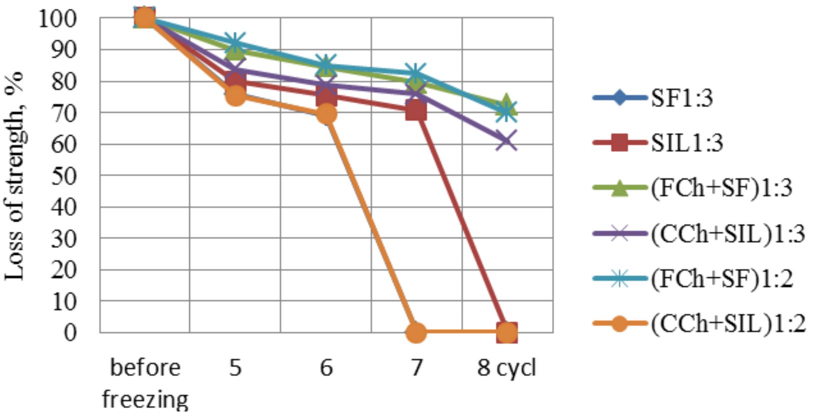

Figure 6.6 Influence of alternating freezing-thawing cycles on the compressive strength of mortars with variable compositions. Initial strength before the frost resistance test (Table 6.9) is 100%

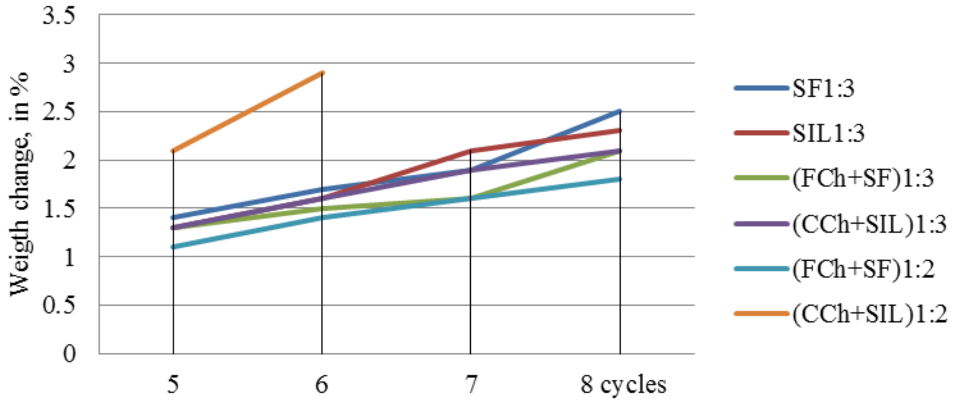

Figure 6.7 Influence of alternating freezing-thawing cycles on the mass change of mortars with different compositions

6.6 Conclusions

The laboratory analysis of lime mortars made using different aggregates showed the improvement of the obtained characteristics. When the mix ratio of mortar is changed to 1:1, 1:2 and 1:3, the compressive and flexural strengths change in relation to the composition of aggregate which agrees with Konow (2003) and Thomson (1999). The compressive strength of mortars with sand is generally the highest with a 1:2 mix ratio and the lowest with 1:3 the point where a considerable increase in water demand also takes place. The mortar containing fine ground chamotte 1:2 (lime: ground chamotte) had the highest compressive strength despite its relatively high water demand while its flexural strength was similar with mixes containing sand. Using coarse ground chamotte considerably reduced flexural strength.

Adhesion strength of fine sand mortars exceeds the adhesion strength of coarse sand mortars and increasing the amount of lime binder improves adhesion strength. Fine ground chamotte decreases the adhesion strength of fine sand mortar while coarse ground chamotte improves adhesion strength of coarse sand and lime-rich mortar that achieves strength analogous to pure quartz sand mortar.

Increasing the relative amount of aggregate in the mortar causes an increase in the density of the mortar, addition of ground chamotte decreases the density of the mortar, use of coarse sand and ground chamotte decreases the density of the mortar.

The sets of tested lime mortars show basically identical capillary water absorption in hardened mortar while water absorption is lowered to certain extent by decreasing the content of sand (1:2). Use of finer sand SF increases water demand. Chamotte decreases the density of mortar and increases water absorption, lime mortar 1:3 (lime: SIL sand) has the highest density and lowest water absorption while assuring very good characteristics as far as historic masonry conservation is concerned.

Water vapour permeability testing established that water vapour diffusion resistance factor μ was 15.7–17.5 in case of laboratory made mortars. Ancient plaster mortar had the lowest water vapour permeability; its water vapour diffusion resistance factor μ was the lowest – 12.4. Water vapour diffusion resistance factor μ is increased if the chamotte with proper size fractions is added to the aggregate mix.

Frost resistance determined by alternating freezing-thawing of the lime mortars was 5–8 cycles. Increasing the content of lime in the mortar and using coarse ground chamotte produces mortar with low density, high water absorption, low frost resistance and low adhesion strength. Lime-rich mortar made with coarse sand and coarse ground chamotte has the lowest frost resistance.

The results show that the composition of ancient plaster mortar from Pöide Church was 1:2.2 (the ratio of lime binder (including indissoluble limestone, clay etc.) to aggregate). The sand used has a high fineness modulus – 1.03. Ancient Pöide Church lime mortar exhibited good behaviour, particularly in terms of capillary absorption.

6.7 Acknowledgements

The authors are grateful to Eldur Karu from Tallinn University of Technology for the help in testing.

6.8 References

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EVS-EN 196-1 Methods of testing cement - Part 1: Determination of strength

EVS-EN 196-2 Method of testing cement - Part 2: Chemical analysis of cement

EVS-EN 933-1Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method

EVS-EN 13139 Aggregates for mortar

EVS-EN 1097-3 Tests for mechanical and physical properties of aggregates - Part 3: Determination of loose bulk density and voids

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7 RESEARCHING MOISTURE CONTENT IN THE MASSIVE LIMESTONE WALLS OF MEDIEVAL CHURCHES WITH THE USE OF MICROWAVE SENSORS

Lembit Kurik

7.1 Introduction

The main building material of medieval churches in Saaremaa and western Estonia is limestone and dolostone in its various forms. Easily tractable Kaarma dolostone was widely used. Rectangular blocks cut from this material were used in crucial parts of the buildings such as corners, arch stones, etc. The same material was also used in sculptural objects. Local lime- and dolostone material was used as well – It was a perfect building material used between the crucial parts built of Kaarma dolostone. Granite was also used in churches in Saaremaa but to a smaller extent (in the basement of some churches, wall material in Püha Church). Typical usage of local building materials is shown in Figure 7.1 depicting the locations on churches involved in the present study and Silurian regional stages in Saaremaa and Muhu Islands. Layers suitable for extracting building materials in Jaagurahu, Rootsiküla and Paadla strata mainly consist of lime- and dolostone. Circular limestone can be found in the Kaugatama stratum – this material was used in walls of Püha Church.

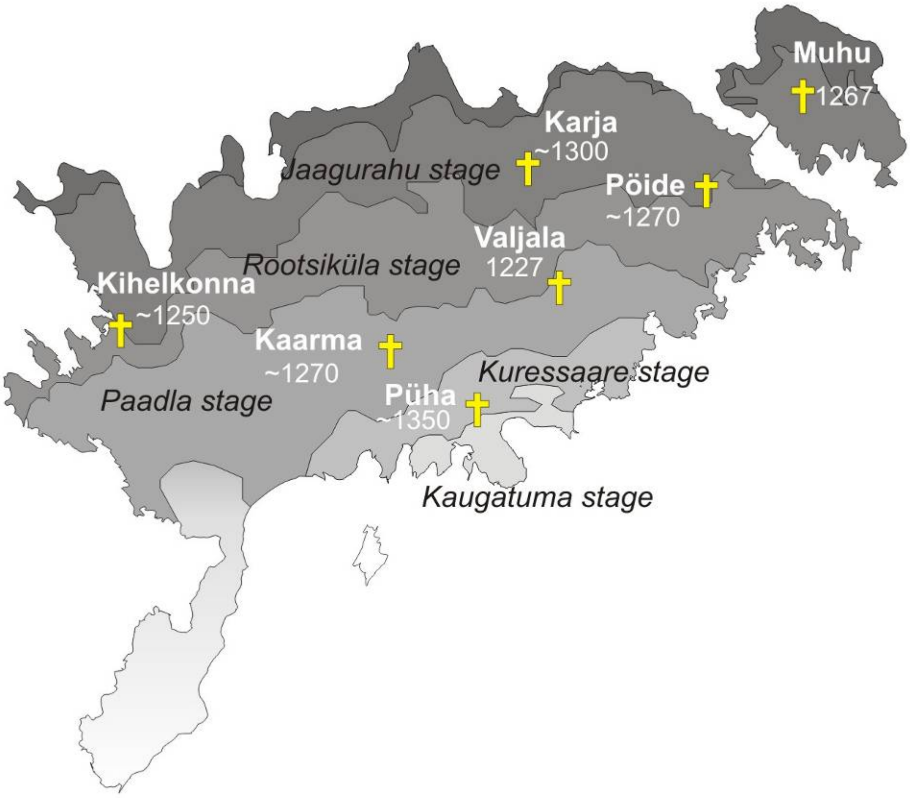


Figure 7.1 Geological map of bedrock and locations of the medieval churches of Saaremaa (Silurian regional stages in italic), modified according to the Bedrock Geological Map of Estonia, © 2011 Eesti Geoloogiakeskus OÜ.

Table 7.1 lists the main moisture-linked properties of the building materials used in the churches included in the present study.

Table 7.1 Main moisture-linked properties of building materials used in the churches included in the present study.

	Density kg/m^3	Porosity, %	Water absorption, %	Natural moisture content %	CaO %	MgO %
Kaarma dolostone (Paadla stage)	2220 [1] 2080-2290 [3] 1960-2240 [2]	21,9 [1]	8,9 [1] 8,9 [3] Up to 10,4 [2]	0,22 [3]	26-31 [3]	14-20 [3]
Vasalemma limestone	2600-2700 [3]		0,9-1,0 [3]		46,4-55,5 [3]	0,3-9,1 [3]
Lasnamäe limestone	2650 [1] 2590-2760 [3]	2,6 [1]	0,9 [1] 1,0-1,9 [3]		44,8-46,3 [3]	4,1-6,8 [3]
Selgase dolostone (Jaagurahu stage)	2230 [1]	21,7 [1]	7,8 [1]			

[1] www.lossikivi.ee/index.php?a=looduskivid
[2] Based on measurements of samples of Kaarma dolomite.
[3] Helle Perens. (2003). Paekivi Eesti ehituses I. Üldiseloomustus. Lääne Eesti. Eesti Geoloogiakeskus.

Estonian dolostone is more porous than limestone. The porosity of dolostone varies from 8.3 to 25% and limestone porosity from 1.5 to 9.5% (Trikkel, 2012). This means that the churches in Saaremaa are built of materials with mostly identical moisture properties: porous dolostone.

Harju-Risti Church, located in a deposit of Ordovician sedimentary rock stratum, uses Lasnamäe- and Vasalemma limestone (Vasalemma marble) as building materials. These rocks are considerably less porous.

The materials used in churches in Saaremaa are porous, no moisture stopping layers were used in basements, the buildings' service was neglected – roofs are leaking, ventilation is accidental in nature. This causes an inevitable problem: high and very mobile moisture content in the walls. Moisture leads to physical, chemical and biological damage. Some typical examples of such damage are shown in Figure 7.2.

Figure 7.2 Typical damage caused by moisture

Water in the walls originates from direct rainfall, capillary water from the surface and from vapour in the air.

Moisture in the wall can be in the form of „pure" water, moisture bound within the cavities in wall materials, crystal water found in some salts or in form of vapour. Such moisture can change state and also move in different directions inside the wall. The movement of free water in walls is mainly caused by gravitational and adhesive forces as well as temperature gradients.
Water vapour is very mobile; its displacement is caused by the vapour pressure gradient. One must also keep in mind the fact that water vapour can quickly condense to liquid form and back. Salts present in wall and their distribution in time makes the big picture even more complex.

Displacement of water in walls is strongly influenced by the properties of the building materials, their non-homogeneity, the temperature of the wall, and the indoor and outdoor climate. Figure 7.3 illustrates these processes.

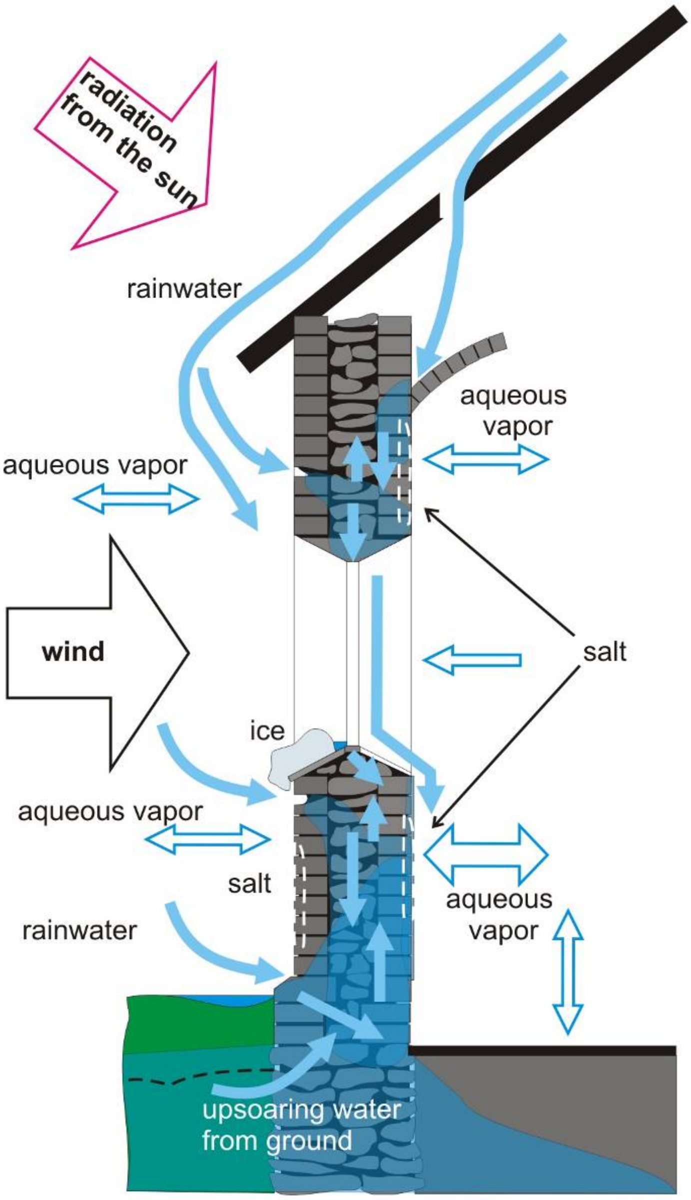


Figure 7.3 Moisture movements in stone walls

This picture is relatively complex and cannot be modelled easily due to the inhomogeneity and complex shapes of walls, as well as because not much is known of the wall's inner structure. Therefore, the main tool for the diagnostics of moisture-related problems of church walls is determining the distribution of moisture in them and its change over time by moisture content measurements. Naturally, only non-destructive methods are acceptable.

7.2 Microwave moisture measurement method

A number of methods exist for the measurement of moisture content. Only non-destructive techniques are applicable for measurements in medieval churches: namely dielectric, nuclear magnetic resonance (NMR), neutron scattering or x-ray scattering techniques (Kupfer, 2005). In this study, one of the dielectric methods, reflection of the microwaves from the tested material, was used. This method utilizes the well-known fact that the dielectric permittivity of water is much higher than the permittivity of most building materials and microwave reflection coefficient depends directly of dielectric permittivity of the material (see Figure 7.4).

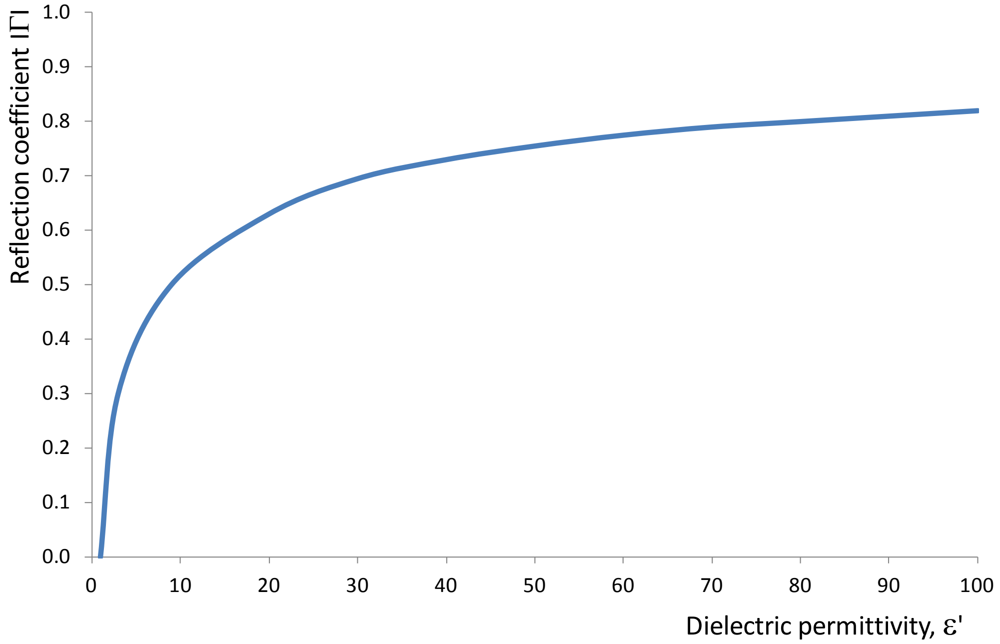


Figure 7.4 Relationship between the dielectric permittivity of a material ε and its microwave reflection coefficient (Agilent, 2005)

High frequency methods are more suitable for dielectric moisture measurements due to the influence of conductivity of water and of salts, dissolved in water is lower at high frequencies. Results are also affected to some extent by the dependency of water dielectric permittivity on temperature (see Figure 7.5). This method is only applicable at temperatures above 0 C, because ε of ice is ~3.5, comparable to dielectric constant of building materials. It is not possible to measure the crystallised water found in some salts or a water layer with a height of ~2...3 molecules adsorbed in pores of building materials (Kaatze, 2005). This means that the size of pores in building materials (i.e., the area of pores per volume unit) affects the results for some extent.

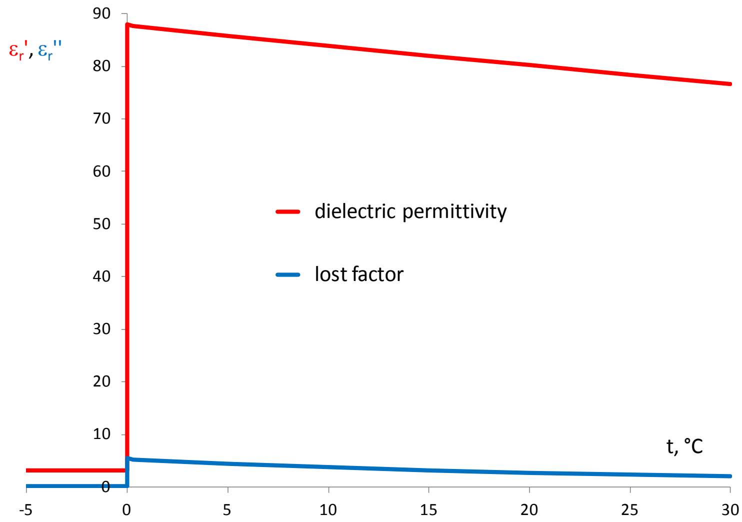


Figure 7.5 Temperature dependency of dielectric permittivity of water and ice at 2.45 GHz. (calculated on the basis of Kaatze, 2005)

For this project, a Moist 200 handheld moisture meter with surface and volume type measuring heads (Figure 7.6 and Figure 7.7) was used.

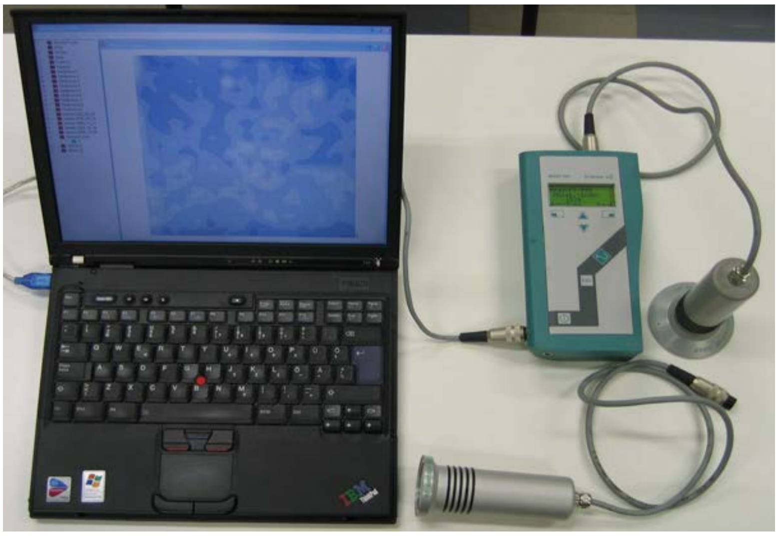


Figure 7.6 Handheld moisture meter with a computer and measuring heads

Table 7.2 Measuring heads of the handheld moisture meter

	 MOIST R	 MOIST R2	 MOIST D	 MOIST P	 MOIST S
Penetration depth up to	3 cm	7 cm	11 cm	30 cm	80 cm
Measuring volume	20 cm³	150 cm³	2 l	10…15 l	40…50 l
Accuracy, %	0.1 … 0.5	0.1 … 0.5	0.2 … 0.5	0.2 … 0.5	?
Moisture range on dry basis, %	0 - 400	0 -100	0 -100	0 - 400	0 - 400
Moisture range on wet basis, %	0 - 80	0 - 50	0 - 50	0 - 80	0 - 80

7.3 Calibration

The moisture measurement sensor heads were calibrated by the manufacturer for calcareous sandstone, sandstone, old bricks, bricks, clinker, soft wood and concrete for certain density values. The sensor head Moist S (with penetration depth up to 80 cm) had no factory calibration. Additional calibrations are needed for Saaremaa dolostone and North Estonian limestone if moisture content measurements in absolute values are required (presently only relative values are displayed on moisture maps):

- The sensor heads were calibrated for Kaarma dolomite
- 3 cm thick dolomite plates were used for the calibration
- The moisture content of the samples was measured gravimetrically
- Dolomite and limestone are not homogenous and therefore the calibration does not allow for very accurate measurements of real objects
- The averages of several measurements were used
- Calibration for the sensor head Moist R gives differently tractable results and needs additional investigations

7.4 Measurement procedures

- Raster measurements, in general with 1 m steps
- Moisture index measurements
- All values are averages of 3 measurements
- Moisture content was calculated from the moisture index according to the calibration curves for Kaarma dolostone
- A raster map of the moisture content was generated (MS Excel)
- For data analysis, averages at different heights were calculated

Figure 7.7 presents a typical moisture content map with 1 m measurement steps in horizontal and vertical directions. The colour indicates moisture content values in 2% steps. The red values on the left side of the chart are the average moisture content at different heights from the floor and the average moisture content for the entire measured wall.

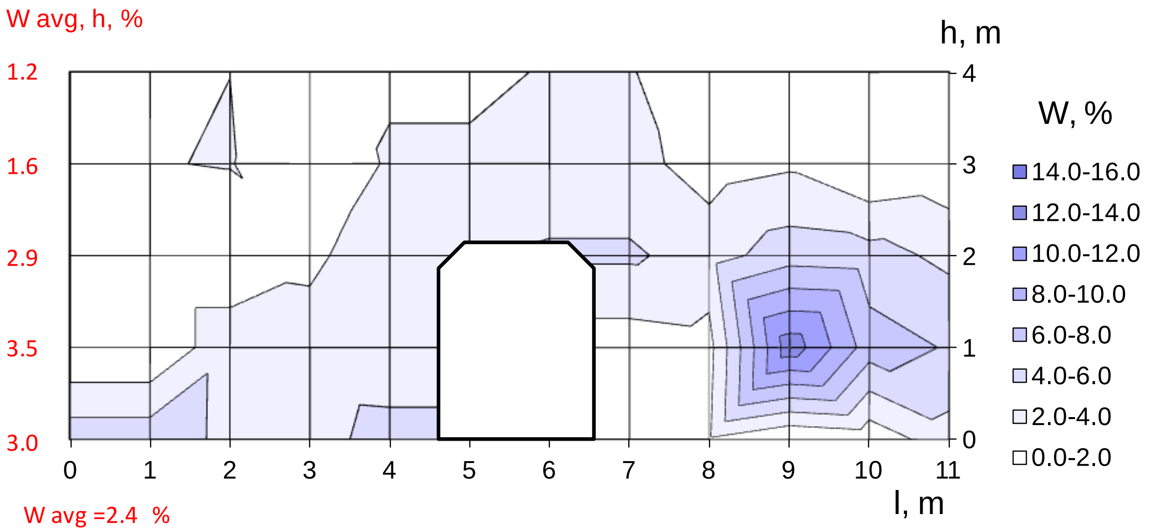


Figure 7.7 Typical moisture map, darker blue areas are more wet; h and l – wall dimensions in horizontal and vertical directions; W – moisture content by weight on dry bases, W avg, h – average moisture content h meters from the floor; W avg – average moisture content of the entire wall

7.5 Measurement history

Moisture content measurements in churches in Saaremaa have been carried out since 2005 – that is, since before the beginning of the present project. The Moist 200 device described above with a Moist P measuring head was used. These measurements gave a moisture index (a number from 0 to 4000, higher number corresponds to higher moisture content) as the result since the measurement head had not been calibrated for the moisture contents of dolo- and limestone. Moisture distribution maps constructed as a result of these measurements give a good overview of the nature of moisture problems. Measurements began in Kaarma and Kihelkonna Churches. Püha, Muhu, Karja and Harju-Risti Churches were later added to the observation list. The measurements were generally carried out once a year. Measurements at Valjala and Pöide Churches were added for the present project. Special attention was paid to Püha Church where seasonal changes of walls moisture content were measured. More complex sensors giving information about in-depth moisture distribution in walls were used.

7.6 Overview of the measurements

7.6.1 Muhu St. Catherine's Church

The main building materials of the Muhu church (Figure 7.8) are Kaarma dolomite, local limestone and Gotland limestone. Measurements were made with a Moist P sensor head (measuring depth up to 30 cm).

In Figure 7.9, we see a typical image of rising damp. No essential changes since 2011. The other measured walls are similar: no damp areas around the buttress and internal corners of outside walls, no differences in moisture distribution in the walls in different cardinal directions. Starting from the 2 m level, the walls are dry.

The main reason for this is that the church is equipped with a rainwater system and the church walls are in good condition on the outside. The main moisture problems include condensed water caused by high indoor humidity and upsoaring moisture (Figure 7.10).

Figure 7.8 Muhu Church in 2013 and 1957 (photo: A. Uuetalu)

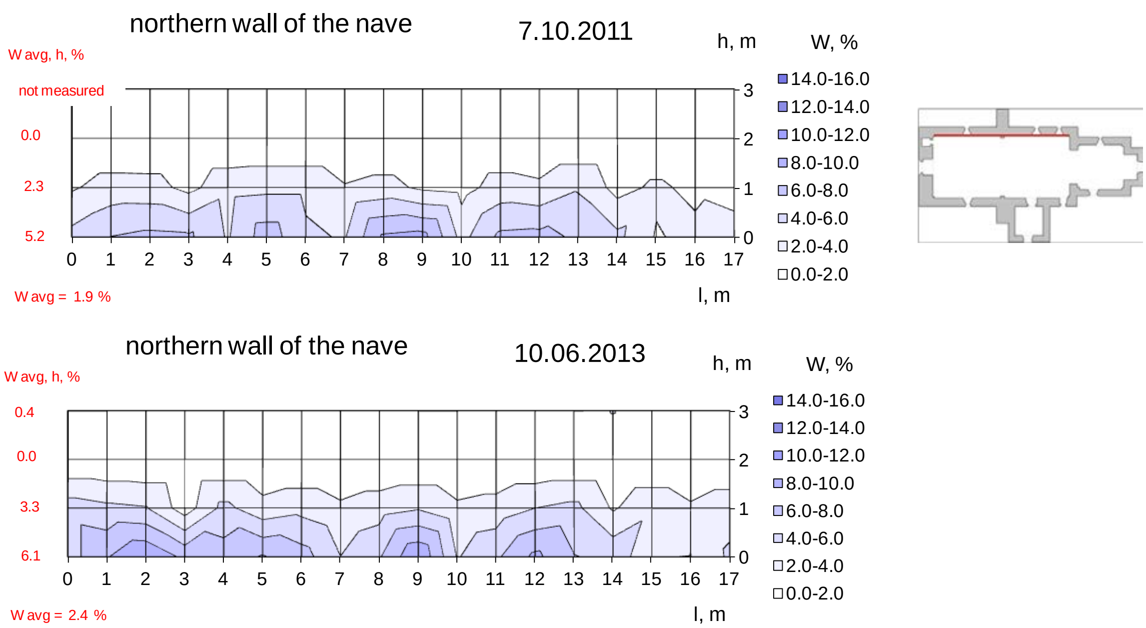


Figure 7.9 Typical picture of the upsoaring rising moisture in Muhu Church

Rainwater system Condensed water Algae growing on rising dump

Figure 7.10 Gutter and biological damages caused by condensed and upsoaring water

7.6.2 Karja St. Catherine's Church

The main building material of Karja Church (see Figure 7.11) is Kaarma dolostone. A new roof was built in winter 2010/2011. Measurements were made on 17.08.2012 and 14.06.2013 with a Moist P sensor head with penetration depth up to 30 cm.

For comparison, old measurements from 10.07.2011 are presented in Figure 7.12. Average moisture content of the measured walls: 2011 – 4.7%, 2012 – 3.1% and 2013 – 3.6%, at the floor level, 7.1%, 4.7%, 6.1%, and at 3 meters from the floor, 3.0%, 1.5% and 1.2% correspondingly. We see some improvements after the construction of the new roof, mainly above the 2 m level from the floor.

Figure 7.11 Karja Church in 2013 and 1924 (photo: H.Kjellin)

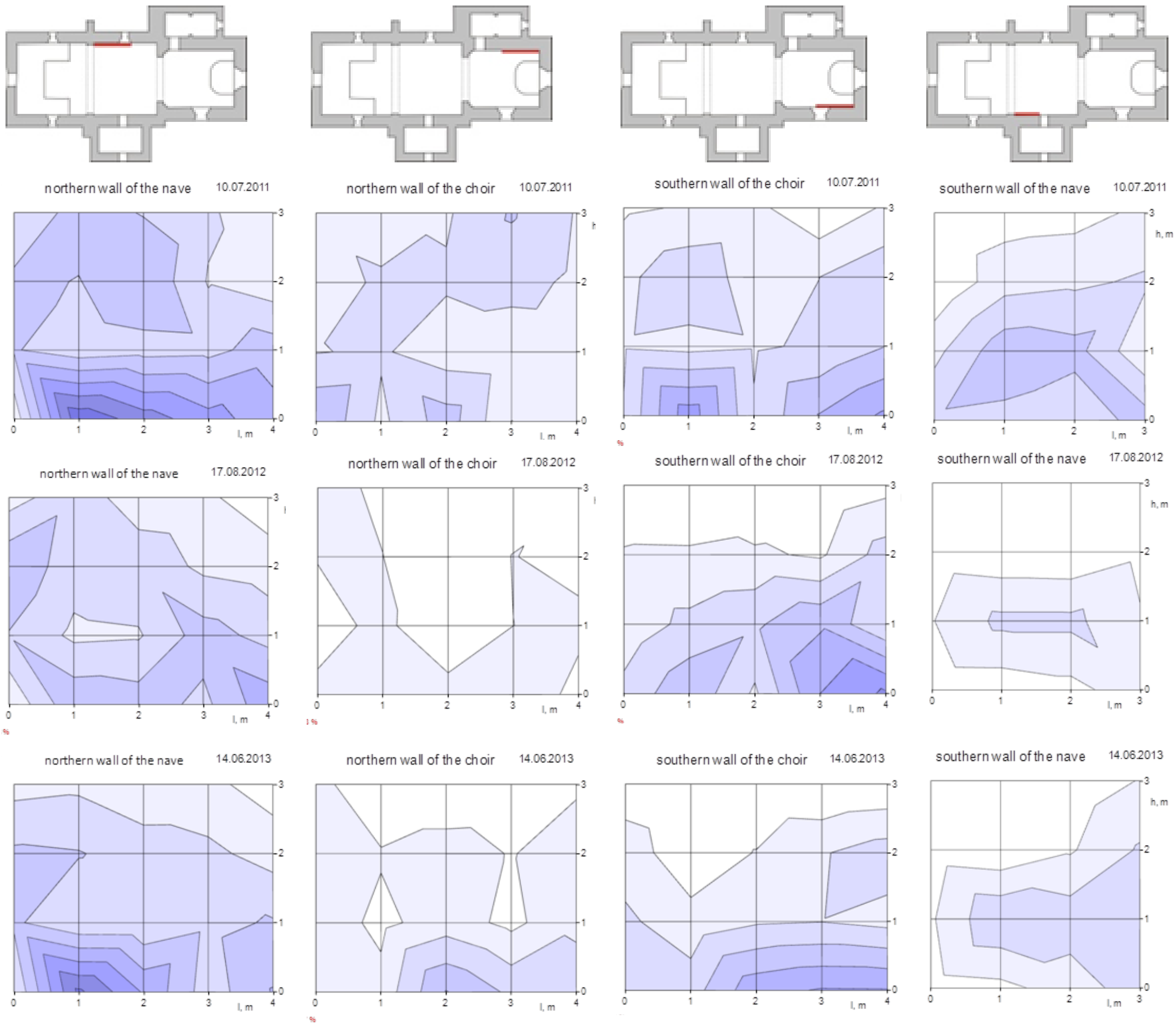


Figure 7.12 Moisture distribution in July 2011, August 2012 and June 2013

7.6.3 Valjala St. Martin Church

The main building materials of the Valjala Church (Figure 7.13) are Kaarma dolomite and local limestone (Valjala dolostone). Measurements were made on 07.07.2012 and 12.06.2013 with a Moist P sensor head with a penetration depth of up to 30 cm.

Only on the moisture maps of the northern and eastern walls of the choir we see the typical picture of upsoaring moisture (Figure 7.14). The other walls are wet at all measured heights. It means that moisture penetrates to the inside faces of the walls from the outside through the massive walls. The moisture picture remains unchanged over the year.

Figure 7.13 Valjala Church in 2013 and 1971 (photo: V. Raam)

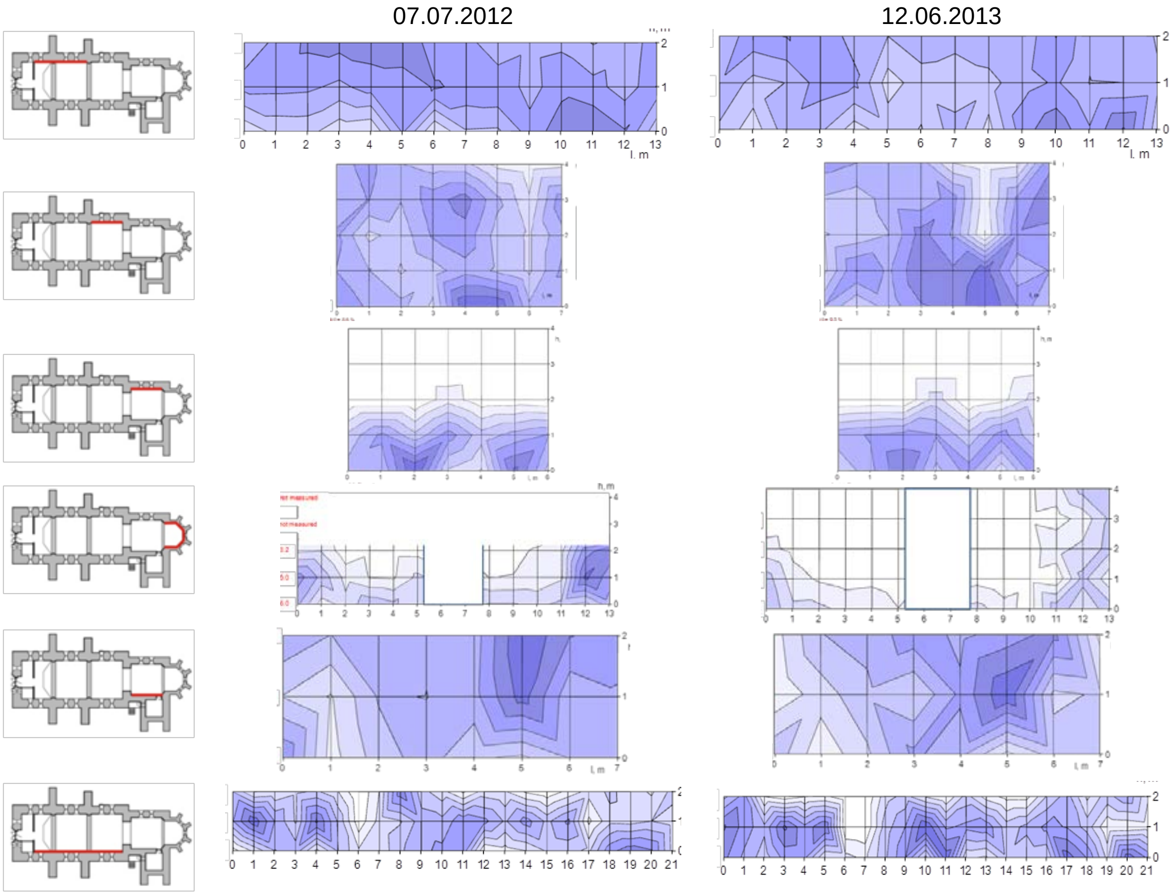


Figure 7.14 Moisture distribution in July 2012 and June 2013.

7.6.4 Pöide St. Mary Church

The main building materials of Pöide Church (Figure 7.15) are Kaarma dolostone, local limestone (dolostone from Jaagurahu and Rootsiküla stages), detrital limestone from Gotland and bricks. Measurements were made on 05.07.2012, 13.06.2013 and 5.07.2013 with a Moist P sensor head.

Presently, part of the northern wall of the church is sheltered by a temporary awning. The moisture map of the inner wall behind the shelter shows relatively low moisture content. The walls higher and to the west from the shelter are wet. The eastern wall has a surprisingly high moisture content induced probably by capillary forces. The southern wall has a small wet area with an extremely high salt content. The salting points to high mobility of moisture in the mentioned region.

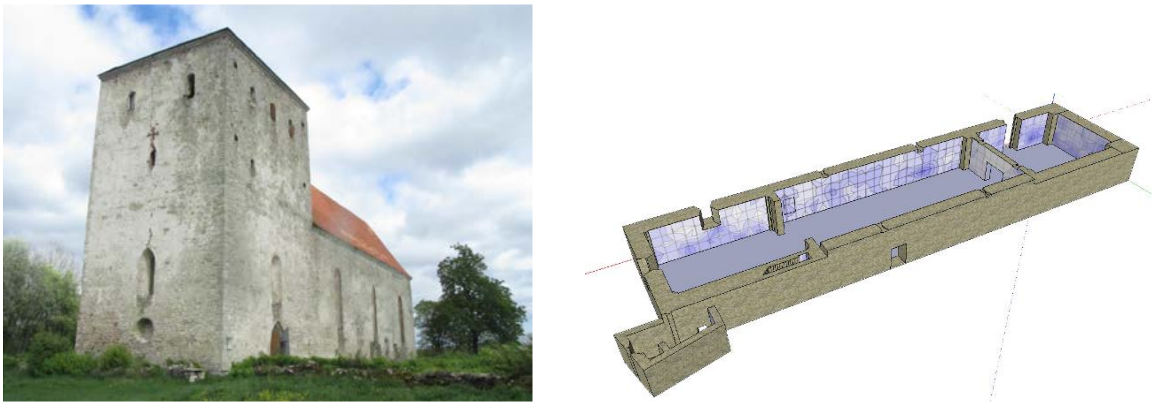


Figure 7.15 Pöide Church in 2013 and moisture measurements presented in a 3D model (made with Google SketchUp, © *Google 2010*)

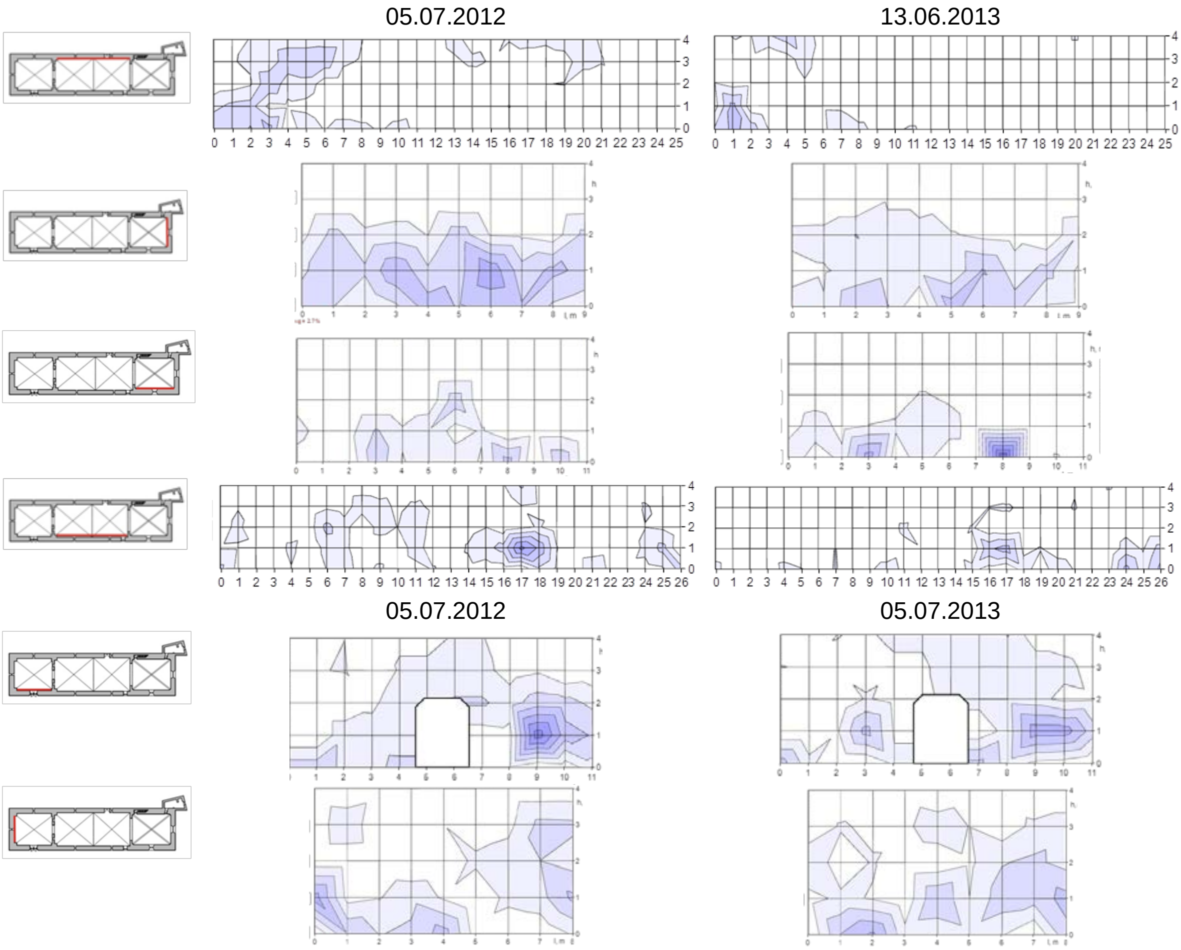


Figure 7.16 Moisture distribution in July 2012 and June 2013

7.6.5 Püha St. James Church

Main building materials of Püha Church (Figure 7.17) are Kaarma dolostone, circular limestone, local limestone. Measurements were made on 05.07.2012, 13.06.2013 and 5.07.2013 with a Moist P sensor head.

Short history of the restoration of Püha Church:

- 1954 – rebuilt counterfort at the southern side
- 1959-1960 - plastering and whitening of the inside and outside walls
- 1990 – reinforcement and hydro-insulating works in the basement of the church
- 2001-2003 - restoration of the roof
- 2007 - restoration of the walls of the choir and of the nave under the loft

On the northern wall of the choir, measurements were made with sensor heads with different microwaves penetration depths. For comparing, old measurements from 25.10.2007, 9.08.2007, 10.09.2008, 21.10.2009, 21.10.2010, and 6.10.2011 (over 5 years) are presented.

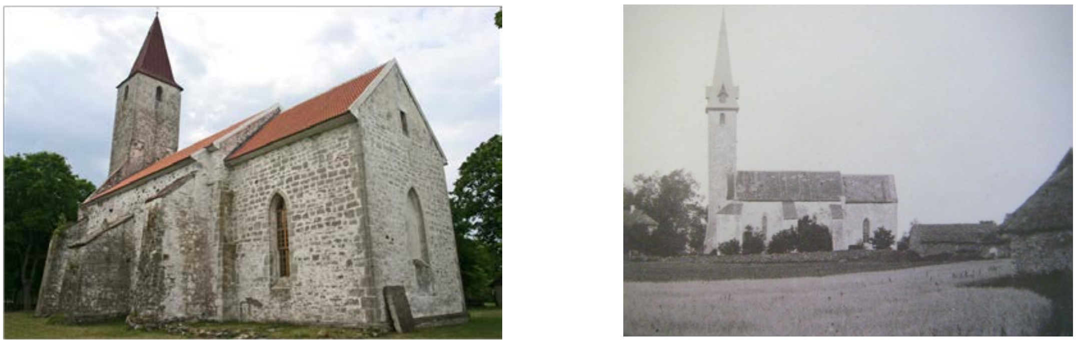


Figure 7.17 Püha Church in 2013 and 1909 (Pajur 2006)

Northern wall of the nave

Moisture content decreased after the renovations in 2007, see Figure 7.18 and Figure 7.19. Big seasonal changes can be observed. The maximum moisture content occurring in July can be explained by the great relative importance of condensed moisture and hygroscopic moisture in the wall's moisture balance. Dampness rising from the ground can be clearly seen. The effect of the counterfort on moisture content can also be seen from the maps. The results obtained in winter 2013 may be distorted due to the partial freezing of the wall.

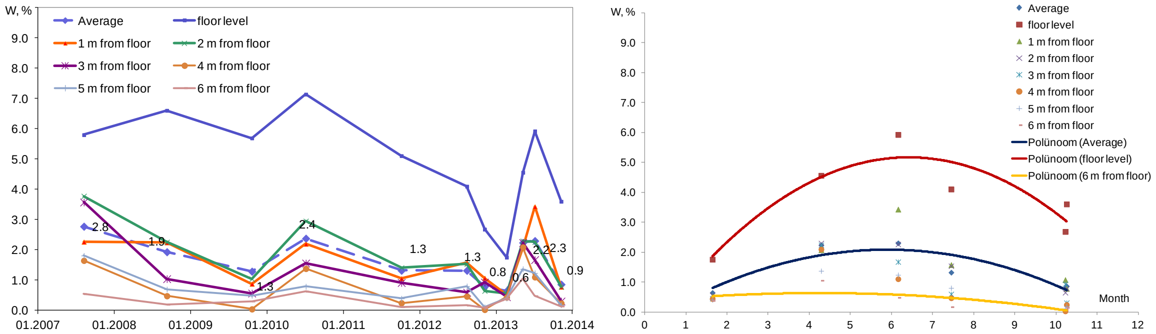


Figure 7.18 Average moisture contens of the northern wall of the nave

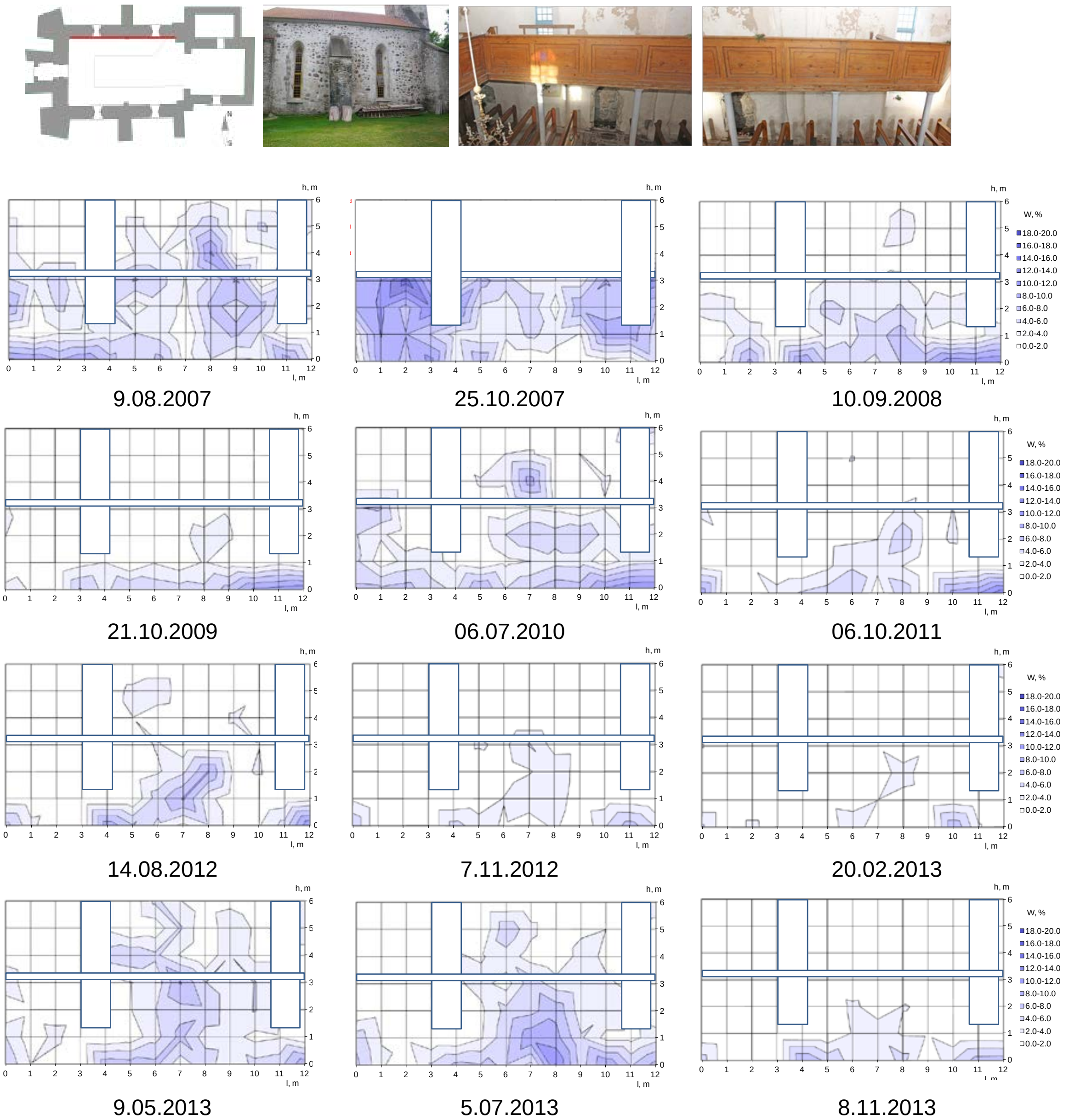


Figure 7.19 Moisture maps and the average moisture content of the northern wall of the nave

Northern wall of the choir

Seasonal changes in the moisture content of this wall are smaller (Figure 7.20, Figure 7.21), probably due to fact that it is an inner wall. One can observe an anomalous wet point that has not changed much in 7 years, the origin of which is not clear. Algae growth in that region shows that it cannot be an anomaly caused by some larger metallic object disturbing microwave penetration. There are several possible explanations: leakage of water from some higher location through cavities in the wall, some bigger building block in the wall with good thermal contact with the ground predisposing accumulation of condensed moisture, or an aquifer in the ground acting as a source of capillary moisture.

The state of the wall before restoration (algae blooming) is typical for the presence of moisture in capillary form so the last explanation is probably the most likely (Figure 7.22).

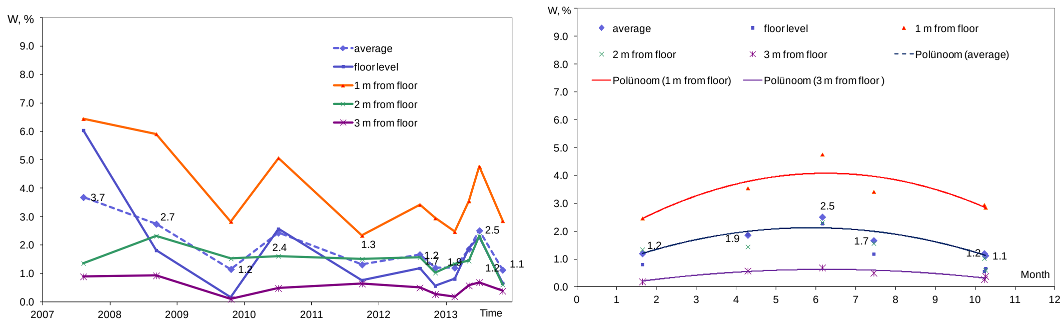


Figure 7.20 Average moisture content of the northern wall of the choir

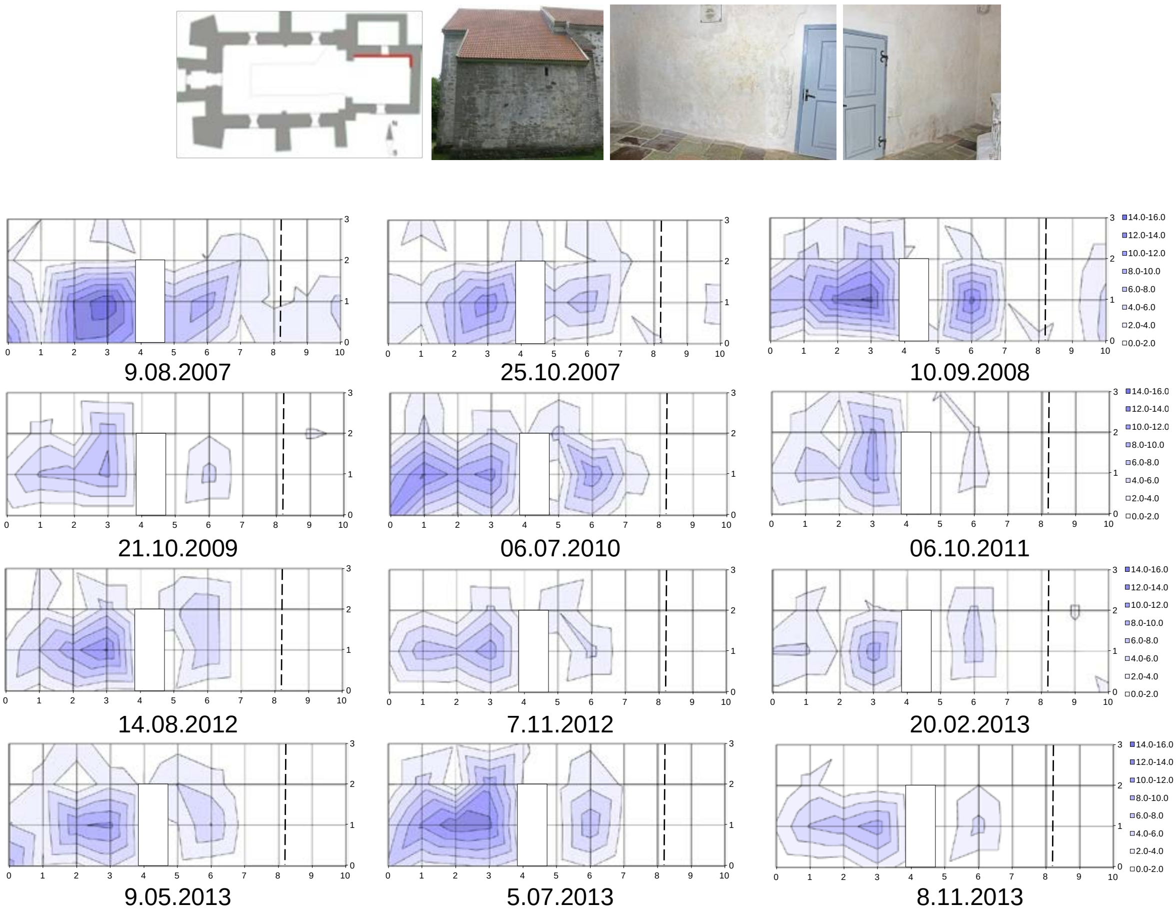


Figure 7.21 Moisture maps of the northern wall of the choir

Figure 7.22 Northern wall of the choir before restoration in 2007 and mould on the wall in 2013

Southern wall of the choir

The condition of the wall has improved significantly; see Figure 7.23 and Figure 7.24. The wet region below the window is caused by moisture originating from the broken window-board and wall, see Figure 7.25.

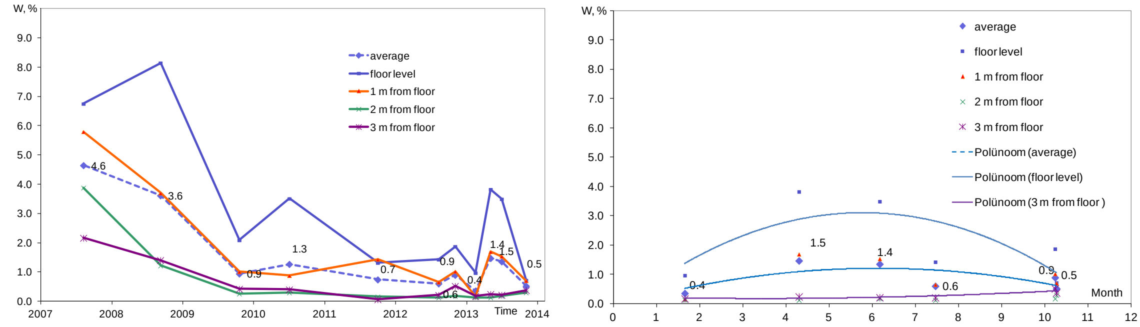


Figure 7.23 Average moisture content of the southern wall of the choir

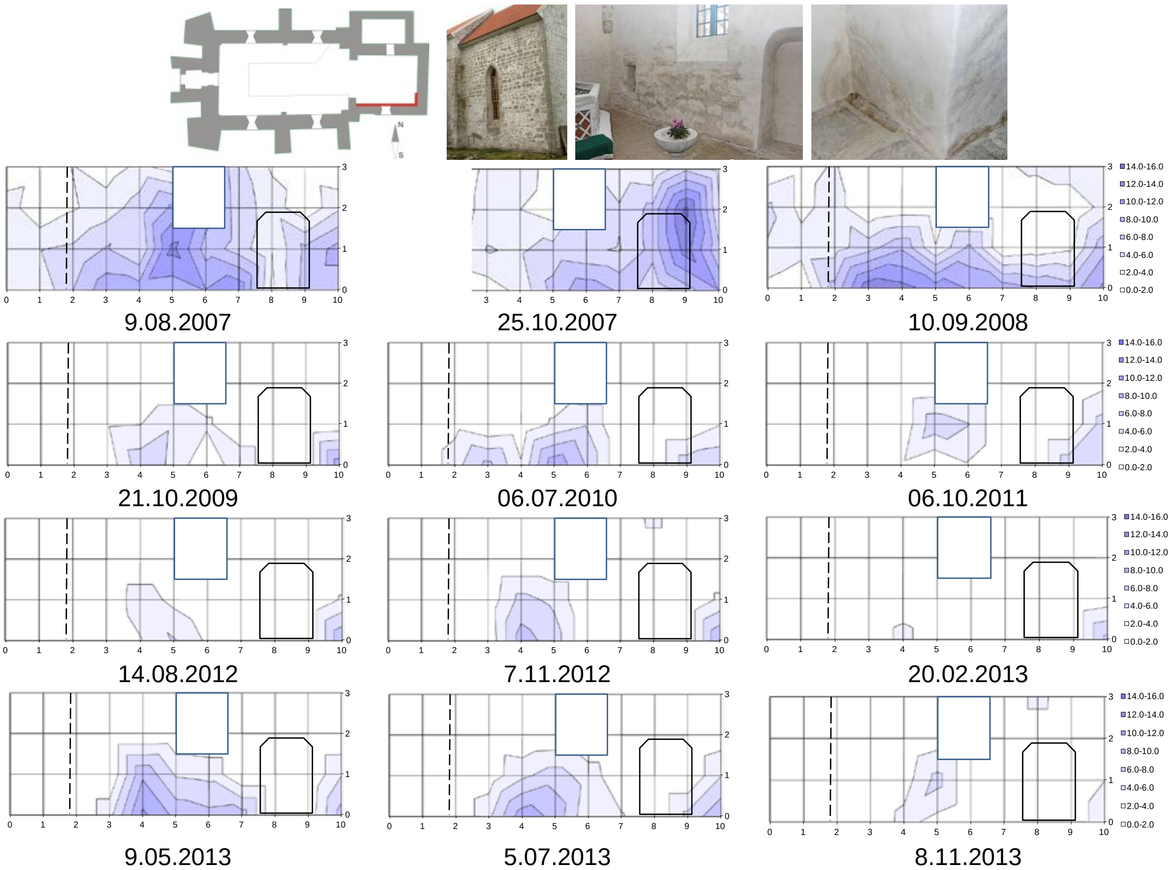


Figure 7.24 Moisture maps and the average moisture content of the southern wall of the choir

Figure 7.25 Broken window sill and wall, green algae in the same location on the inner side of the wall

Southern wall of the nave

Relative moisture content is high, see Figure 7.26, Figure 7.27. It drops in the winter but is still relatively high. A distinctive feature of this wall is a relatively dry wall at higher altitudes to the east of the counterfort. Obvious reason: the counterfort prevents water brought by western winds and coming from the roof (inclined to the east) from reaching the walls. This proves the assumption that most of the moisture in the wall originates from the roof.

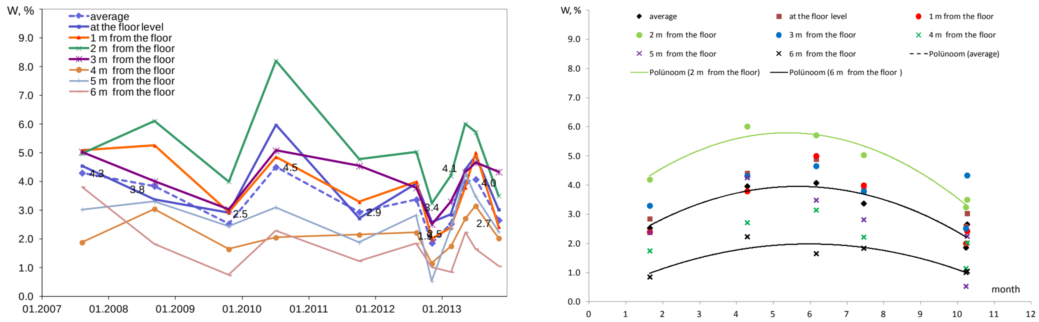


Figure 7.26 Average moisture content of the southern wall of the nave

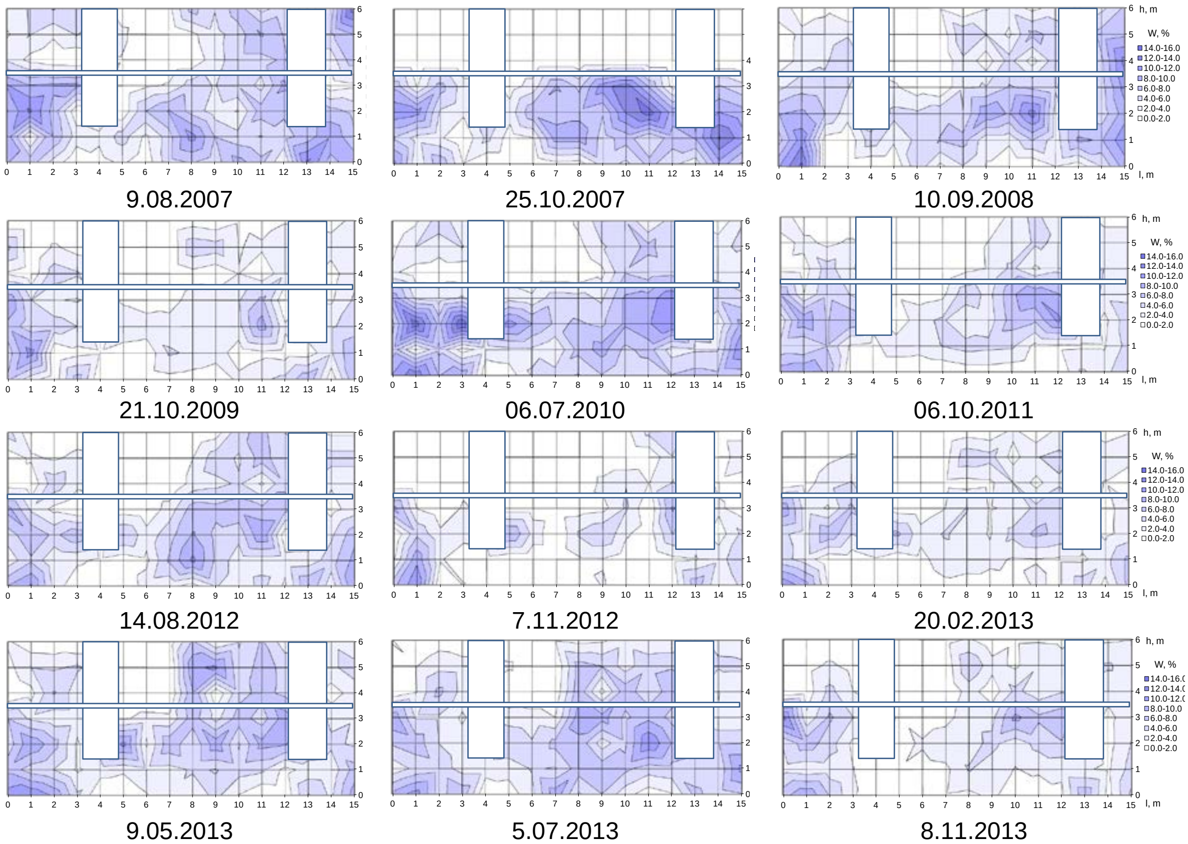


Figure 7.27 Moisture maps of the southern wall of the nave

7.6.6 Kaarma Church of Saints Peter and Paul

The main building material of Kaarma Church (Figure 7.28) is Kaarma dolostone. Measurements were made on 10.05.2013 and 16.08.2012 with a Moist P sensor head with a penetration depth up to 30 cm. Old measurements from 27.05.2005, 16.08.2006, 15.10.2007, 9.09.2008, 23.10.2009, 8.10.2010 and 9.07.2011 (7 years) are presented for comparison.

Figure 7.28 Kaarma Church in 2013 and ? (unknown)

Northern wall of the nave

The moisture content of the walls has not changed much since 2005, although seasonal changes are still visible. Moisture reaches the highest point in May, suggesting that condensed water has a big role in moisture balance.

Excessive salt content and air movement in the church amplify these processes. Nevertheless, the main source of moisture is probably rainwater falling from the roof to the walls. The high level of moisture, its distribution (the higher, the more wet) and the accumulation of salts (salts have to get out from wall to its surface somehow) should confirm this assumption.

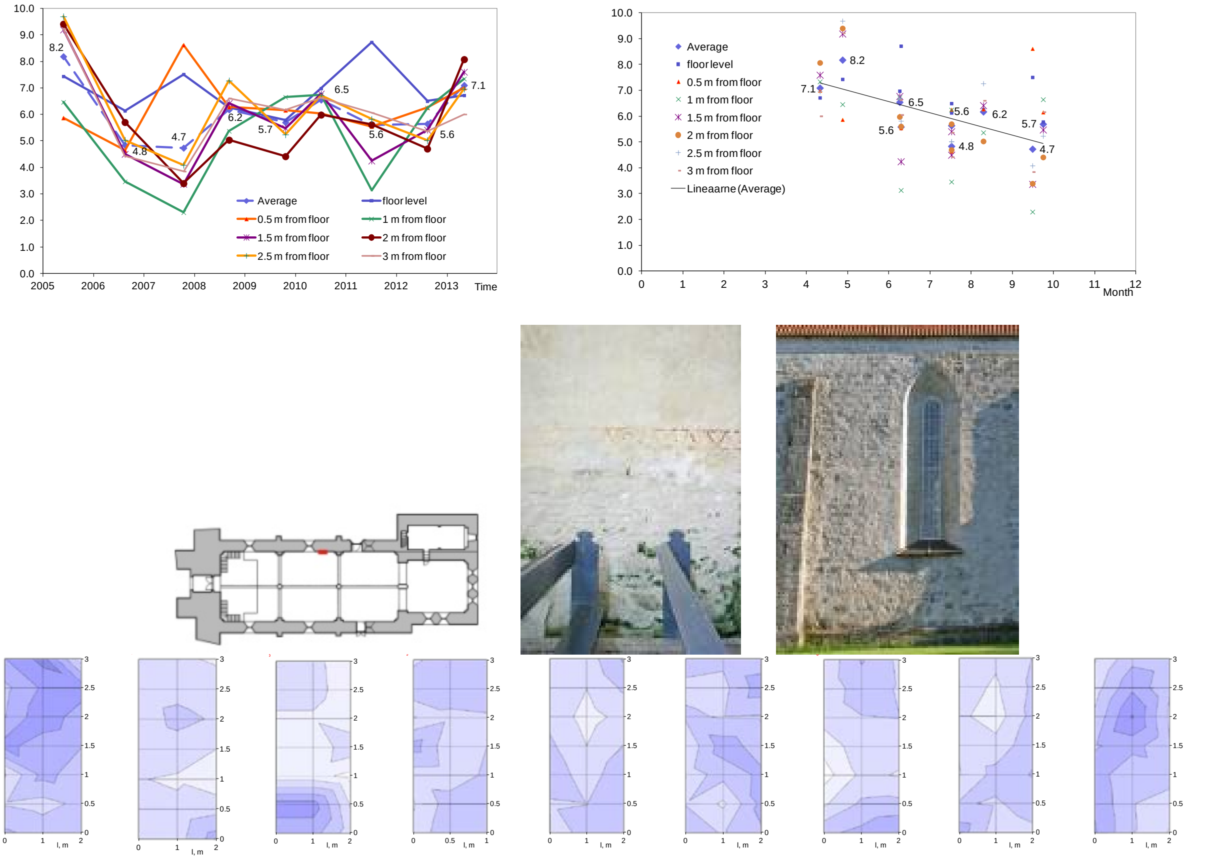


Figure 7.29 Average moisture content and moisture maps of the northern wall of the nave

Southern wall of the choir

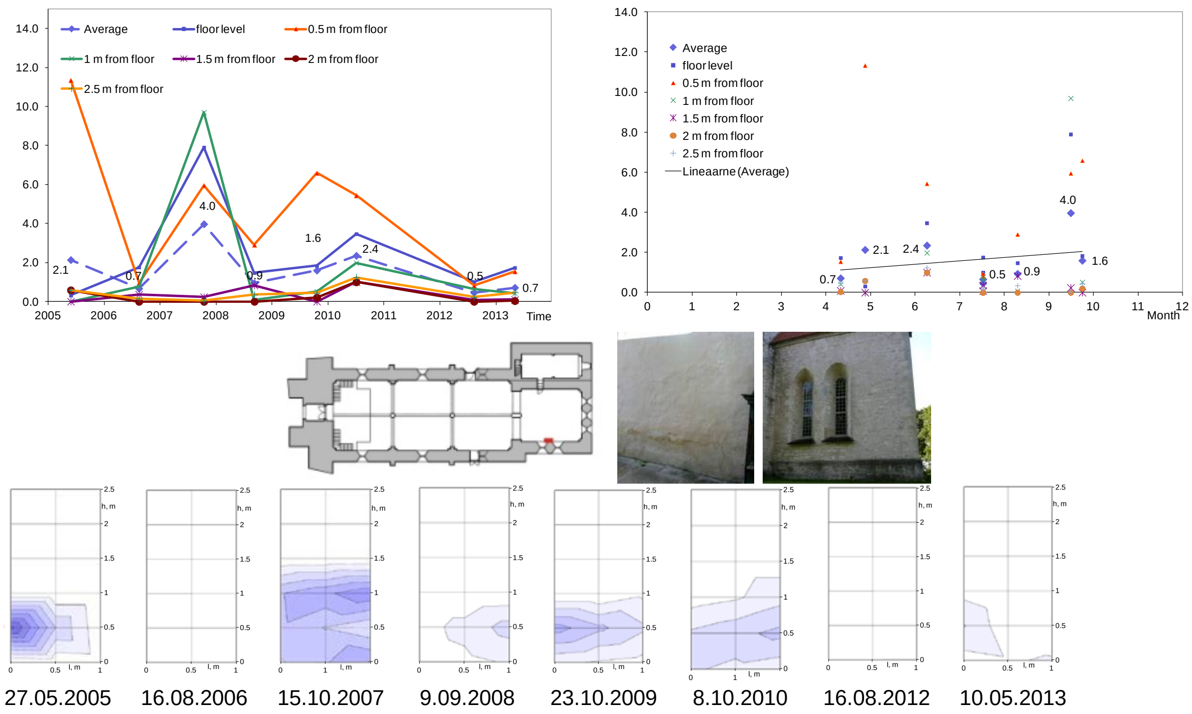


Figure 7.30 Average moisture content and moisture maps of the southern wall of the choir

Part of the eastern wall of the nave

Overall moisture content is low with a clear maximum in the beginning of summer. Moisture originates mainly from water condensed on the walls. Since the roof of the church is inclined to the south and north, water from the roof cannot leak to the eastern walls. Capillary moisture is poorly defined, can be seen at a height of up to 1 m.

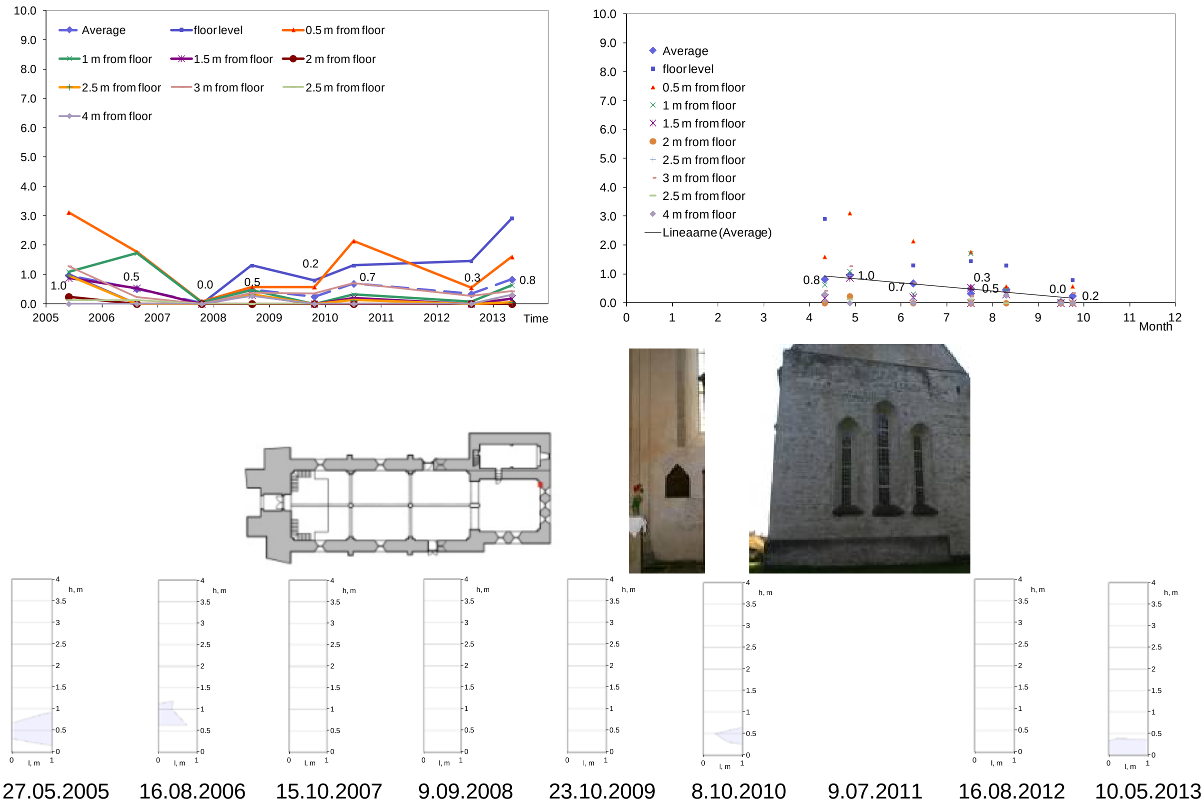


Figure 7.31 Average moisture content and moisture maps of the eastern wall of the choir

Part of the eastern wall under the window:

Moisture content of this part of eastern wall is also low. There is a clearly visible cranny in the wall that can be observed on moisture distribution map (especially up to year 2008, after which the window sill above the wall was coated with a temporary cover). Despite the low moisture content, a crucial crystallization of salts (mainly KNO_3) on walls takes place and damages the surface of the walls. The clear decomposition of a test patch made by restorers in 2005 can be seen in Figure 7.33.

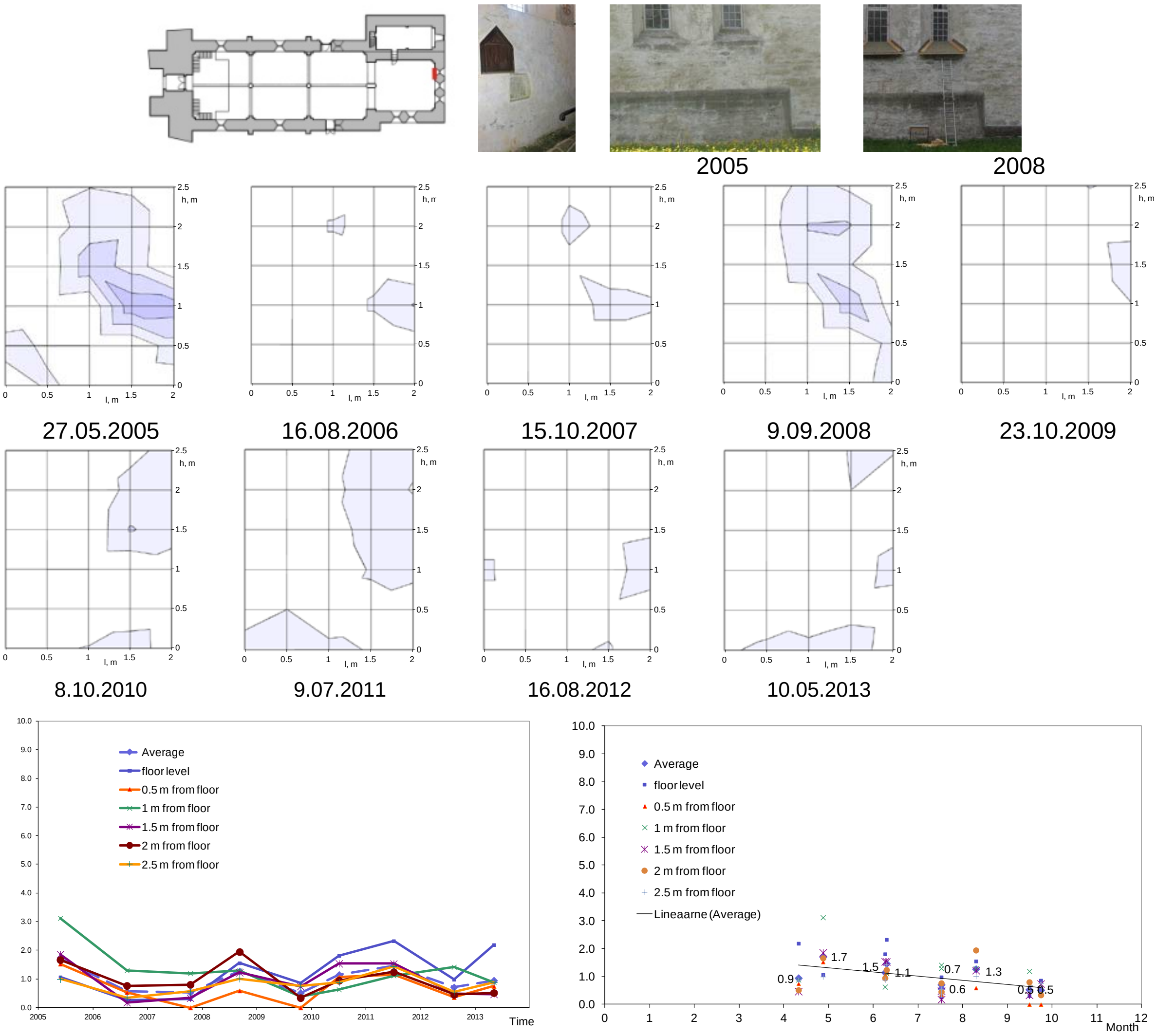
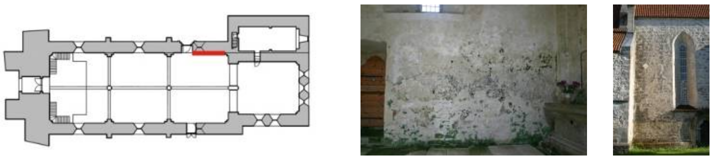


Figure 7.32 Moisture maps and the average moisture content of the eastern wall of the choir

Figure 7.33 Lime paint test patch

Northern wall under the window (in the nave):

A temperature map (10.05.2013) of the church's northern wall is presented in Figure 7.35. The same data is shown on the indoor and outdoor climate graph. The temperature of a significant part of the wall is below the dew point for air both in and outside the building, making the conditions very favourable for water vapour condensation (on the wall). Moisture content deep inside the wall is lower than in surface layers (Figure 7.34) (except at 7 cm where the calibration is not very accurate for plaster). It means that condensed water is the main water source for this wall.



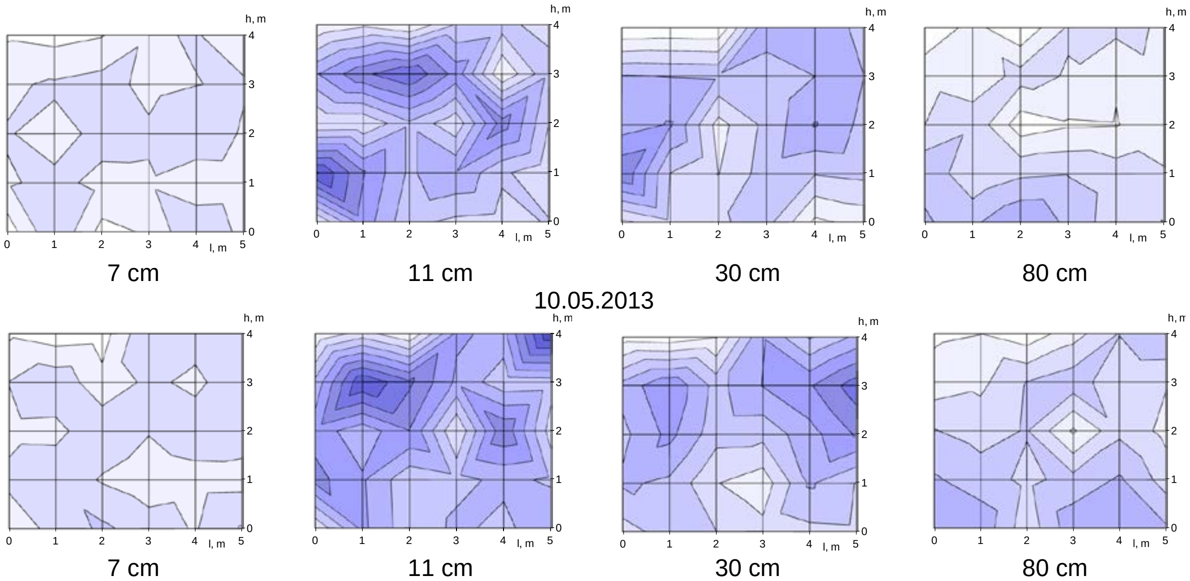


Figure 7.34 Moisture maps at depths up to 7 cm, 11cm, 30 cm and 80 cm

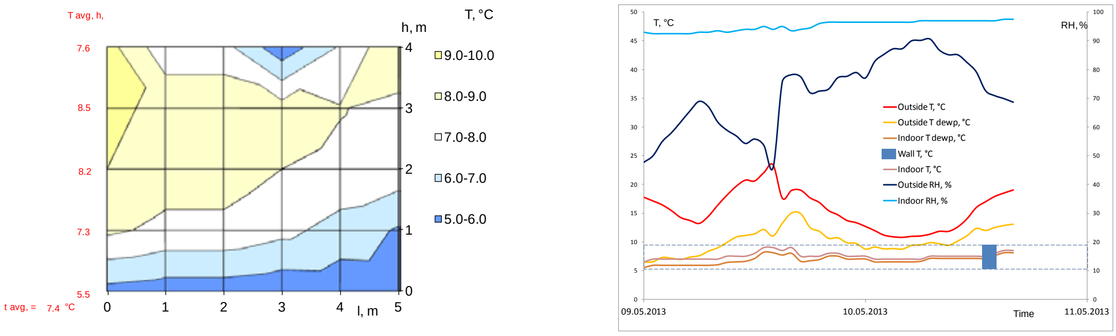


Figure 7.35 Northern wall under the window, 10.05.2013

Southern wall of the nave

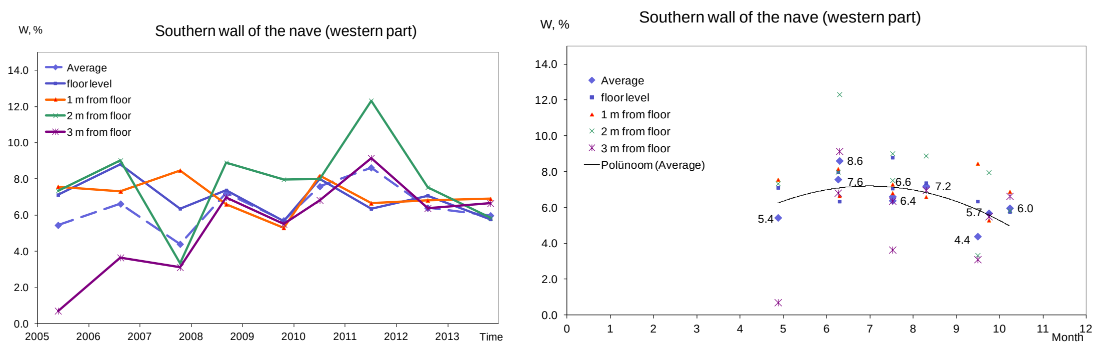


Figure 7.36 Average moisture content of the southern wall of the nave

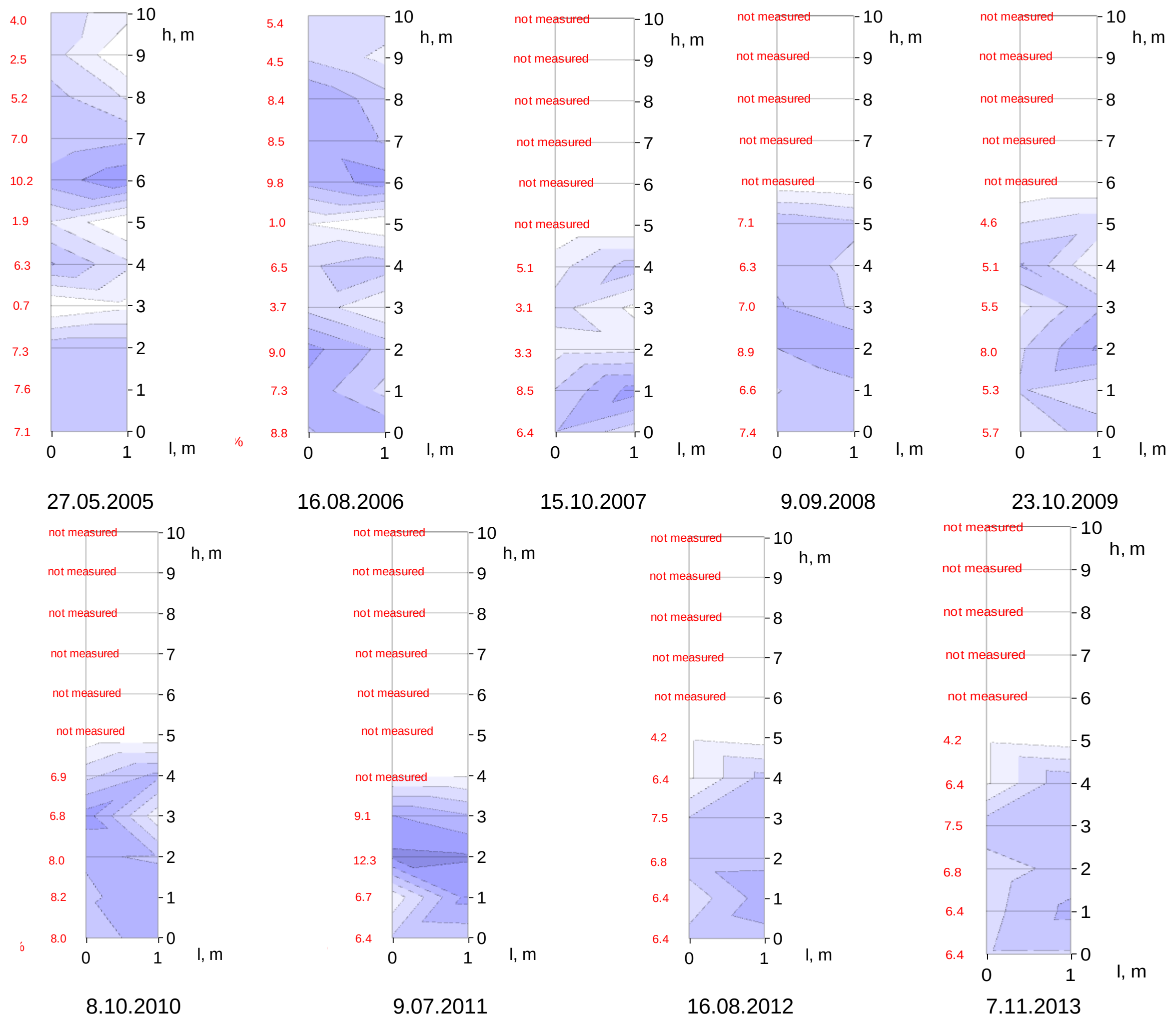


Figure 7.37 Moisture maps of the southern wall of the nave

7.6.7 Kihelkonna St. Michael's Church

The main building material of Kihelkonna Church is Kaarma dolostone. Measurements were made on 11.05.2013 and 15.08.2012 with a Moist P sensor head with a penetration depth of up to 30 cm. Old measurements from 24.05.2005, 18.08.2006, 9.08.2007, 10.09.2008, 22.10.2009, 7.07.2010, 6.10.2011 (7 years) are also presented for comparison. Short history of the restoration of Kihelkonna Church (kirikud.muinas.ee):

- 1938 – the lower part of church is covered with wooden panels
- The beginning of 1980s and the end of the 90s: plastering the walls from the outside
- 2001 - 2004 – renovation of the roof: all covering stones were replaced
- 2002 – 2006 – conservation and renovation of the choir room, removal of plaster (with cement add-on) and wooden panels from the walls of the nave

Southern wall of the nave:

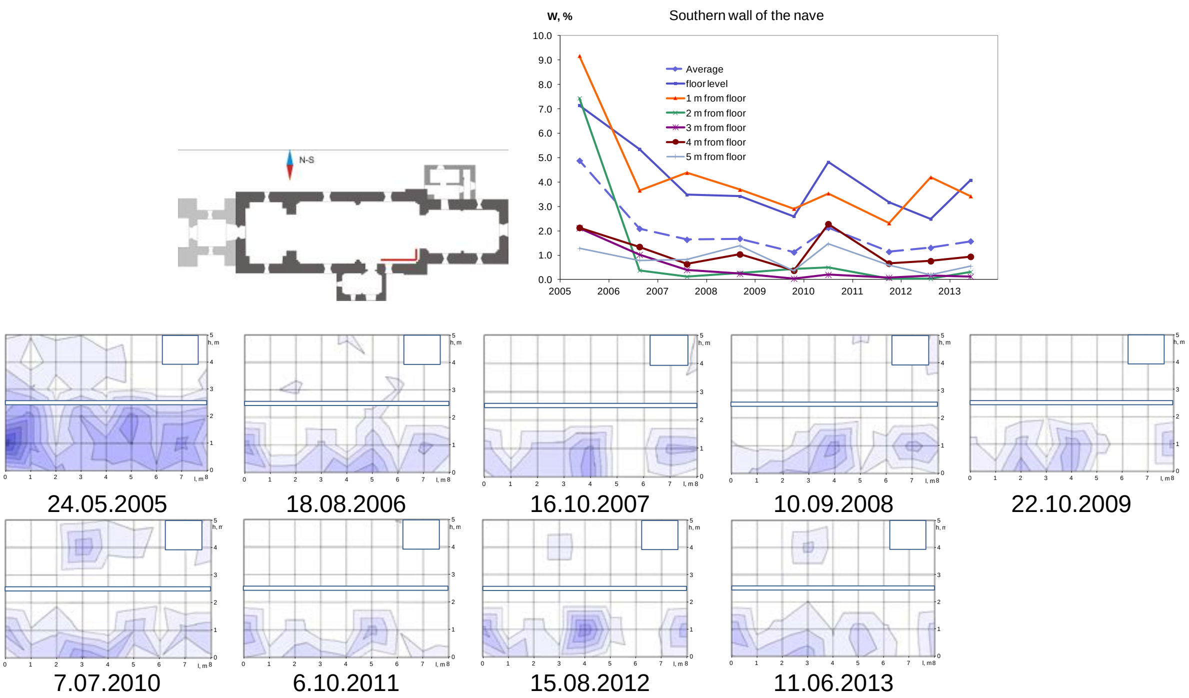


Figure 7.38 Moisture maps and the average moisture content of the southern wall of the nave

Southern wall of the choir

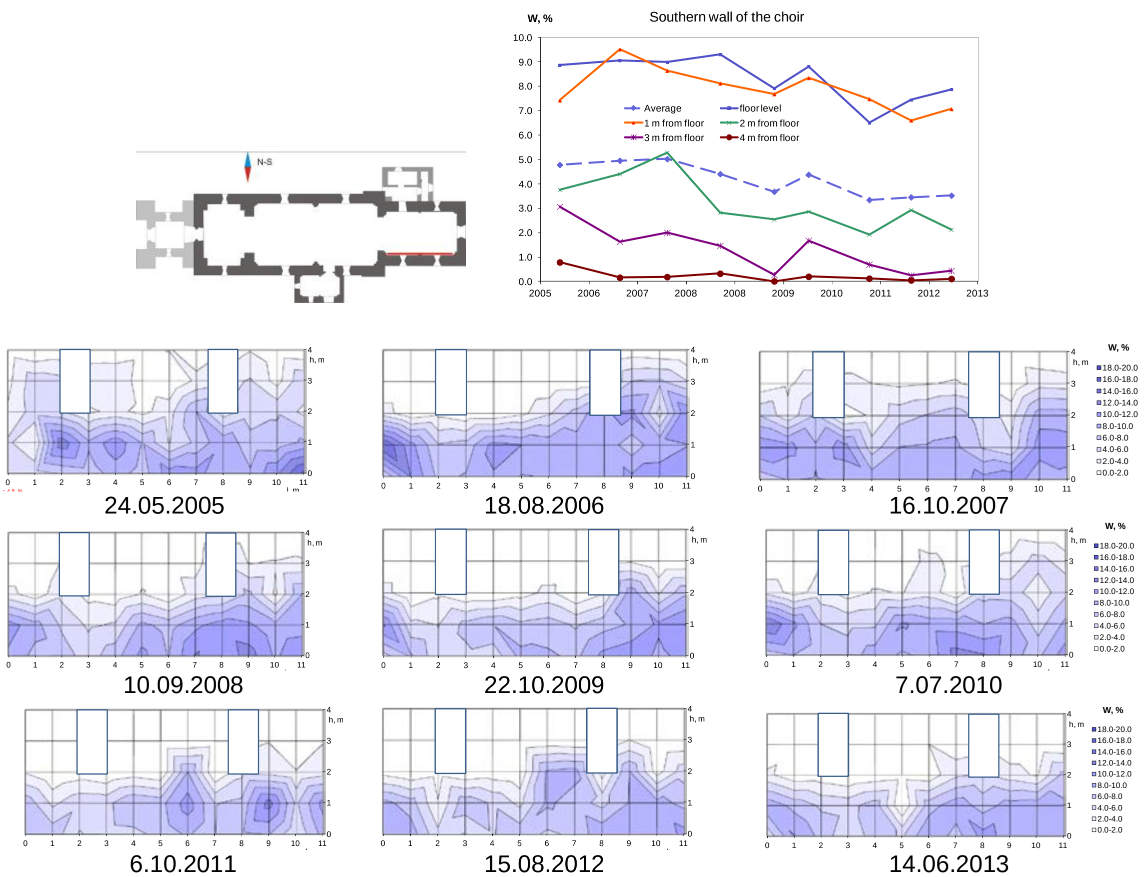


Figure 7.39 Moisture maps and the average moisture content of the southern wall of the choir

7.7 Conclusion

Mapping the moisture content of walls by means of microwave reflection is a sensitive and very suitable method for diagnosing the moisture problems of national heritage buildings.

Measurements can be performed quickly and without affecting the object. Graphically presented results are easily readable even for a non-specialist and significantly facilitate the analysis of the problem.

The indirect nature of the measurements somewhat lowers the reliability of the results for some particular points due to the following issues: non-homogenous and probably unknown wall structure (interfering elements such as wires, tubes, metal parts present in the object), the absence of calibration for some particular building material, etc. One disadvantage of the described method is the fact that moisture can be measured only in the form of free water. Other methods (like NMR) should be used for measuring the content of ice or crystal water. Problems in calibrating the Moist R measuring head described earlier show that the quality of the calibration is crucial for getting correct results. The calibration can be misleading due to the presence of water in the test (stone) plate, the orientation of the sensor head (since microwave radiation emitted from the Moist R is partly polarized) or for some other unknown reason. Averaging allows getting results with higher reliability.

The measurements carried out in churches in Saaremaa show some general trends. The main source of moisture in the churches included in the present study is water condensing on walls in late spring–early summer. This common problem of all non-heated churches was confirmed by the analysis of the dynamics of the moisture content of walls. Moisture reaches the maximum level in May/June/July, decreasing first in higher locations (of walls) where the temperature is higher (see Figure 7.18, Figure 7.29, Figure 7.32). Moisture content is also higher in places where large quantities of rain water fall on the walls (see Figure 7.37, Figure 7.29, etc.).

The eastern walls of the churches (Figure 7.31, Figure 7.32) generally not suffering from rain water falling from the roof, the parts of walls protected by gutters (Figure 7.9), and those located away from the direction of predominant winds are significantly dryer.

Significantly higher moisture contents can be observed in the parts of walls where the outer protective structures and joints are damaged (Figure 7.24). Rain water leaking into walls shifts the maximum of seasonal moisture content to the summer period or even later (see Figure 7.37, Figure 7.30).

Another source of moisture in all churches included in the present study is the moisture accumulating from the ground through capillary forces. This is clearly visible in Muhu Church with its high moisture content in walls up to 1 meter from the ground. In higher parts, other sources mask the effect of capillary moisture.

Measuring the moisture content of the walls is a good method for studying the long-time dynamics of the walls. It allows evaluating the effects of renovations on the condition of the church and is thus a relevant source of information for planning further stages of renovation works. Since the amount of data gathered during the present study is large, it cannot all be presented in this paper. All the data will be made accessible via the Internet.

To sum up, we present some recommendations for preventing moisture problems in churches and other historical buildings:

- The building envelope (roofs, walls, windows, doors) of the church should be repaired / kept in good conditions;
- Churches should be equipped with rain water systems (gutters with tubing carrying the accumulated water further away). Different means for servicing gutters such as gutter cleaning robots are available.
- The air-tightness of the doors and windows should be improved; ventilation should be increased, especially in the spring–summer period. The simplest solution would perhaps be installing electronic devices for measuring humidity/temperature and giving recommendations (on the basis of the measurements) for when it is safe open church doors and/or windows.
- The moisture resistance of objects protruding from window sills or walls should be significantly improved. In winter, they will be covered with ice and snow, thus creating good conditions for moisture to penetrate. Possible solution: covering the mentioned surfaces with terne plates. Such covers have only a minimal visual effect since they cannot be seen from ground. On the other hand, their overall effect on the building’s “health” is immense.

7.8 Acknowledgements

The author is grateful to Targo Kalamees, Paul Klõšeiko, Simo Ilomets, Endrik Arumägi, Jaanika Saar, Üllar Alev for their help in the research.

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8 ENERGY AND INDOOR CLIMATE PERFORMANCE OF HEAT PUMPS AND DEHUMIDIFICATION

Magus Napp, Targo Kalamees

8.1 Introduction

8.1.1 Background

In Estonia, most medieval churches have no heating or any other climate control systems installed; their indoor climate is thus mainly determined by the outdoor climate. Because of the churches' massive stone walls, fluctuations in indoor temperature and relative humidity are much lower than outside. In the summer period, massive walls with high thermal capacity are keeping the indoor temperature lower compared to the outdoor temperature; in the winter period, the indoor conditions are warmer.

It is important to distinguish indoor temperature and humidity from the temperature and humidity of the church's envelope (wall, ceiling, window, floor). It is the lower thermal resistance of these structures and the high moisture content in the walls that causes the high relative humidity in the church. This can result in the relative humidity increasing above the critical limit which can lead to the growth of mould fungi and algae.

Air exchange in old historic churches is subject to natural ventilation and is determined mostly by air leakages in the structure. In the summed period, increased ventilation can bring humid and warm air into the church causing the increase of indoor relative humidity. In the winter period where water vapour content outdoors is much lower than indoors, indoor relative humidity is negligible.

8.1.2 Indoor climate requirements for churches

One major problem in controlling the indoor climate in historic buildings is specifying the appropriate climate (see chapter **Error! Reference source not found.**, **Error! Reference source not found.**).

Today, many of the churches in Europe are heated. For heating, many different solutions have been introduced: warm air heating, floor heating, infrared radiant heating, radiator panel heating, convector heating, local heating. These heating solutions are often installed to ensure thermal comfort for people. However, heating for thermal comfort can also damage the church.

There is a lot of literature about damage to church buildings and their interior related to heating systems. Damage to walls, ceiling and paintings and deterioration of stained glass have been described the most often. Damage to historical organs and church interiors has often been ascribed to heating systems. Contamination by soot and dust related to heating systems like floor heating has also been described (Shellen, 2002).

The best conservation strategy is to act in order to prevent damage. Climate control, when properly used, is an efficient and cost-efficient method for preventive conservation. Heating used to control relative humidity for preservation purposes is called conservation heating. The basic principle of conservation heating is to control the temperature inside a building in order to keep relative humidity within given limits.

There are some limitations to the use of conservation heating. When the RH is too low, the temperature can only be reduced to the level determined by the ambient temperature and/or the temperature of the interior surfaces. In the winter, conservation heating may result in uncomfortably low temperatures, even below 0 °C. In summer, conservation heating may result in uncomfortably high temperatures. (Broström, 2008)

Assuming that the humidity by volume inside the building is the same as on the outside, the temperature required to maintain a specified relative humidity can easily be determined. In most buildings however, humidity by volume is higher inside than outside. For buildings in general, this can be related to the use of the building, but in many historic masonry constructions, moisture continuously accumulates from the walls (Broström, 1996).The evaporation from the walls increases with indoor temperature.

8.1.3 Purpose of the study

In Estonia, medieval churches are mainly unheated and without any climate control. Measurements indicated high relative humidity which favours mould and fungi growth as well as decay of the buildings caused by unsuitable fluctuation in climate conditions. There is a clear necessity for climate control systems in the churches. To identify the most suitable ones, research is needed (measurements, calculations and simulations). At the moment, climate control systems have not been studied adequately in non-heated churches.

The purpose of this study was to:

- Conduct climate measurements and provide an overview of the indoor temperature and relative humidity in a medieval rural church.
- Test and compare indoor climate control systems, air-to-air heat pumps and dehumidification in the church.
- Calibrate an indoor climate and energy simulation model for future simulations;
- Compare the performance of the climate control systems (adaptive ventilation and heating) using an indoor climate and energy simulation and assess the efficiency and energy consumption of the systems.

8.2 Methods

8.2.1 Church of the Holy Cross in Harju Risti

The research was conducted in the Church of the Holy Cross in Harju-Risti.

b)

a) c)

Figure 8.1 a) Western facade of the church; b) Inside the church. Hall; c) Altar

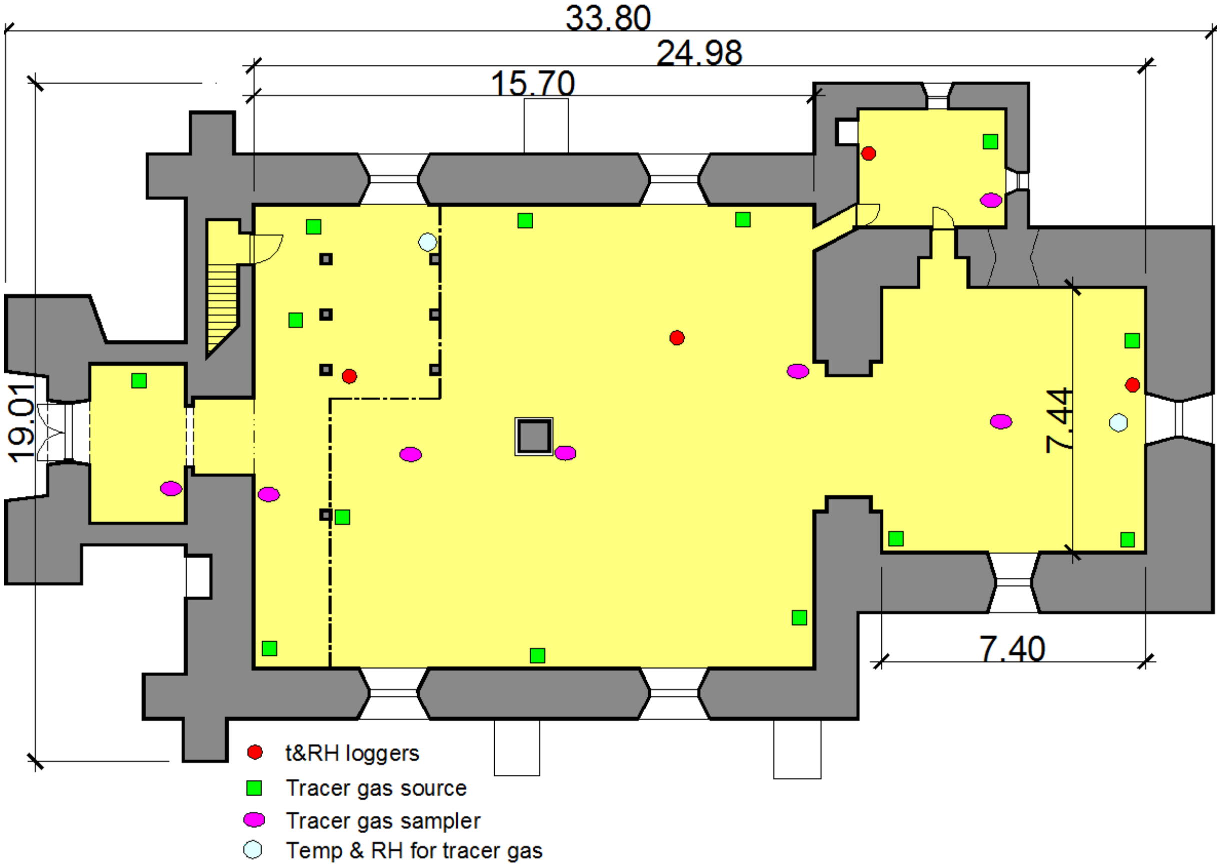


Figure 8.2 Church plan M 1:200, with loggers and tracer gas locations

Field measurements provide the opportunity to acquire realistic results, although changing the boundary conditions and comparison of different versions is difficult. Therefore, in this study, both methods were used.

- Measurements:
  - indoor climate
  - performance of conservation heating
  - performance of dehumidification
- calculations:
  - calibration of indoor climate and energy simulation
  - comparison of different climate solutions

Research questions:

- indoor climate (temperature, relative humidity, air velocity) levels and stability with an air-to-air heat pump for conservation heating and a desiccant rotary dehumidifier;
- energy consumption required for preservation of culturally valuable structures and details with an air-to-air heat pump, a rotary dehumidification and comparison with other heating systems;.
- conditions where it is practical to use heating or dehumidification;
- technical requirements for heat pumps for conservation heating (defrost for outdoor unit, control logic) and for rotary dehumidification equipment;
- visual compatibility of the heat pump and rotary dehumidification with the church interior.

8.2.2 Measurements

Indoor climate measurements

Indoor temperatures and relative humidity have been measured inside the church over long periods of time: May to March; (Arumägi, 2010), April 2012 to December 2013.

For temperature and relative humidity measurements, HOBO U12 data loggers were used (Range: Temp: -20…70 °C, RH: 5%....95%. Accuracy: temp.: ± 0.35 °C from 0…50 °C, RH: ±2.5% from 10% to 90%). Three loggers with a logging interval of 1 hour were installed near the altar and on the balcony (next to organ) and one logger was installed outside the church. Two additional loggers were installed in the hall and the sacristy for the measurement period between May and December, see Figure 8.2.

Air infiltration was measured using the passive tracer gas technique. (Nordtest Method VVS) (16000-8, 2007)

With this technique, it is possible to study the supply rate and distribution patterns of supplied air from the outside to different spaces or the whole building. Measurements can take place over several weeks. Infiltration measurements were conducted in three periods.

The aim of the study was to measure the infiltration of air into the main space of the church. This technique enables the supply rate and distribution patterns of outside air supplied to different spaces or a whole building to be studied.

In the present study, 13 tracer gas sources (type A) were used in the hall of the church; one tracer gas source was used in the sacristy and each of the porch rooms (see Figure 8.2), with tracer gas emission rates adjusted to the room volumes to ensure a homogeneous emission in the whole building. The tracer gas diffuses out of the sources at a known constant rate and is mixed into the room air. The resulting tracer gas concentration in different parts of the building or rooms depends on the ventilation of the rooms. Tracer gas concentration in different parts and locations is measured with a so-called passive sampler (type P).

These measurements provide a good overview of the necessity for improving the indoor climate.

The performance of conservation heating

For conservation heating, an air-to-air heat pump (AAHP) was used. In preparing the study, four different locations for the AAHP were possible:

In the beginning, four different possibilities and locations for the installation of the heat pump’s outdoor unit and two options for the indoor unit were presented. Each one had its own plusses and minuses that needed to be discussed before installation. The Heritage Board considered solution A to be the best: an outdoor unit near the west window on the northern side (Figure 8.4). Technically, however, it was the most unsuitable solution. This solution was still tested out in the hope it would not hinder the research. The indoor unit of the heat pump was installed on a scaffolding to prevent mounting it to the balcony floor.

Two Fuji Nordic heat pumps (RSA12LEC/ROR12LECN NORDIC 5.6kW) were chosen and installed in the hall, under the scaffolding installed in the church for restoration. Indoor and outdoor units were connected through the window. Heat pump installation is shown in Figure 8.5. Heat pump features are shown in Table 8.1.

a) b)

Figure 8.3 Air-to-air heat pump installation: a) outdoor, b) indoor

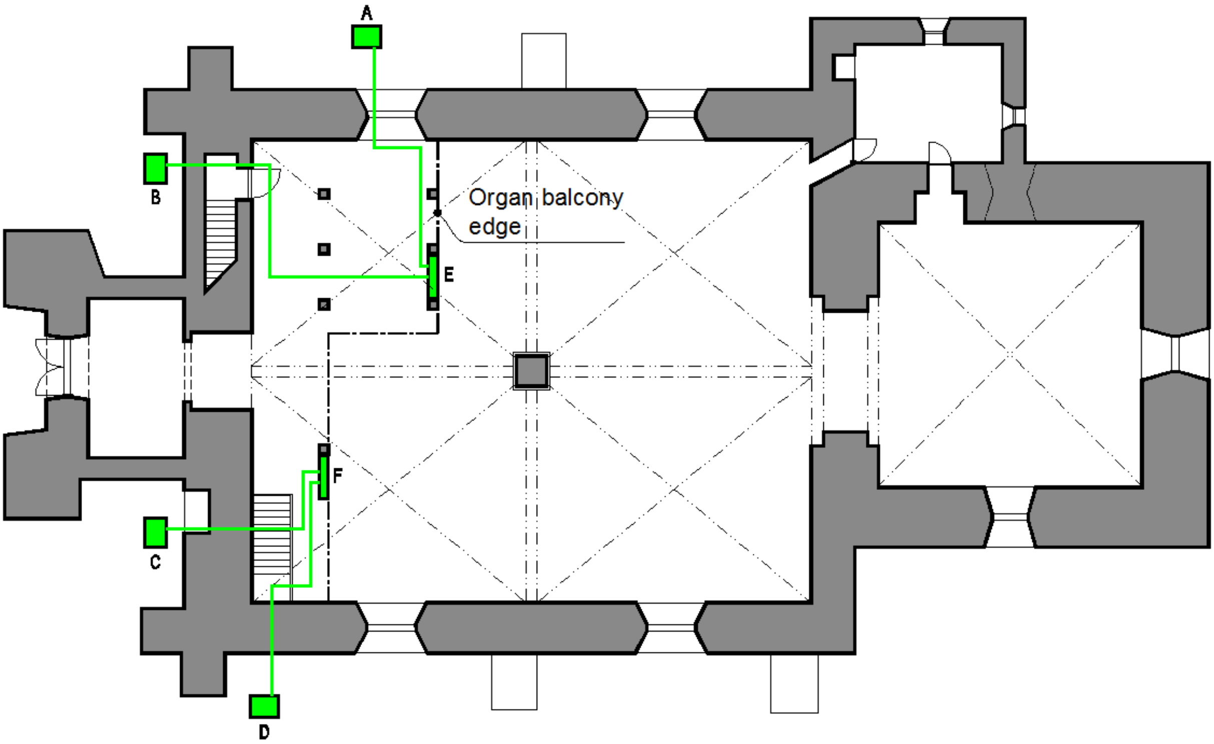


Figure 8.4 Air-to-air heat pump: possible installation solutions

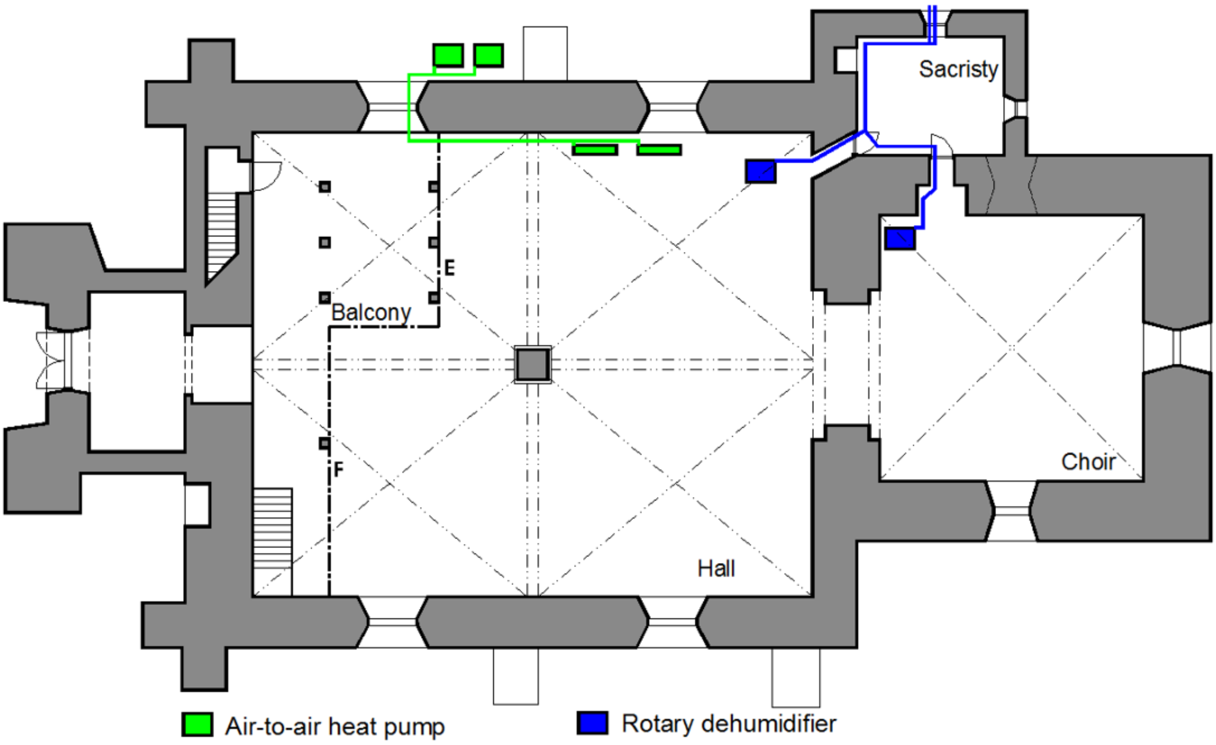


Figure 8.5 Air-to-air heat pump and dehumidification: final installation in the church

Table 8.1 Air-to-air heat pump: technical data.

Indoor unit			
Temperature	-7 °C	0 °C	7 °C
Heating power, kW	4.4	4.6	5.6
Coefficient of performance COP	2.1	2.2	4,2
Electrical power max, cooling (kW)	1.4		
Electrical power max, heating (kW)	2.0		
Dimensions (height x length x depth)	160 x 790 x 202 mm		
Weight (kg)	7.5		
Electricity	1~; 220 V; 50 Hz		
Refrigerant	R410A		
Dehumidification capacity, l/h	1.8		
Noise I/II/III/IV speed, dBA	21/33/38/43		
Working range, cooling: °C	+18…+32		
Working range, heating: °C	(+10) +18…+30		
Outdoor unit			
Dimensions (height x length x depth)	540 x 790 x 290 mm		
Electricity	1~; 220 V; 50 Hz		
Weight (kg)	36		
Noise, dBA	48 (cooling 49)		
Working range, cooling: °C	+10…+43		
Working range, heating: °C	-25…+24		

Heat pump was controlled by:

- relative humidity set to 65…70% in:
  - December 2012 to March 2013
  - May 2013.
- indoor temperature (heating due to conservation works):
  - between March 2013 and May 2013;

Temperature control of the heat pumps was used to heat up the church because restorers started working in the church in the beginning of March 2013.

The control logic of the heat pump controller is presented in Figure 8.6. The controller compares the given temperature and relative humidity settings to the values measured in the church. If the system is controlled by relative humidity, then if the measured indoor relative humidity is higher than the set RH value, the system would start. If the system is controlled by temperature, the controller compares the measured indoor temperature to the pre-set value; if the measured temperature is lower than the pre-set temperature, the system starts. The system is also equipped with freeze protection that protects the system of freezing in low temperatures.

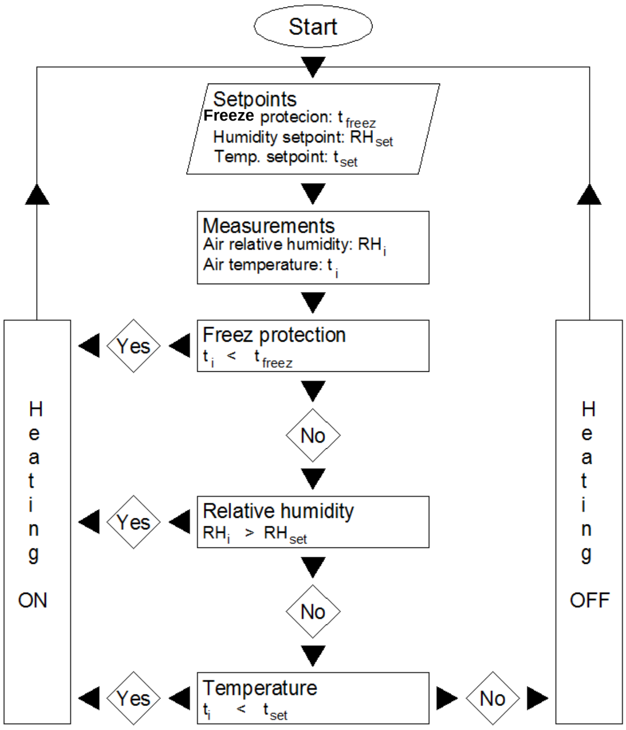


Figure 8.6 Logic of operation of air-to-air heat pump.

Dehumidification

One or two dehumidifiers were initially considered to be installed in the church. One would be installed near the sacristy with the exhaust air pipes exiting the sacristy window. The other dehumidifier would also be located next to the sacristy with the exhaust pipes exiting the sacristy window or near balcony with the exhaust pipes exiting the western window on the northern wall. Because of fresh outdoor air entering the church near sacristy, the best solution was to install one of the dehumidifiers in the choir room and the other in the hall, with both exhaust air pipes exiting through the sacristy window. This solution was the easiest way to install the exhaust air pipes and the dehumidifiers were installed in different rooms providing good airflow throughout the church.

Dehumidifiers reduce the humidity of the air ensuring lower water vapour content in the air as well as lower relative humidity. The dehumidifier does not increase ambient temperature.

There are two main types of dehumidifiers: condensation dehumidifiers and rotary desiccant dehumidifiers. In case of a condensation dehumidifier, air entering the dehumidifier meets a cold coil, the air is cooled and condensate emerges on the cooling coil. Because of the lower water vapour content in the air, relative humidity will decrease.

Rotary desiccant dehumidifiers contain a material that absorbs moisture. The dehumidifier is divided into two sections: process air and reactivation air. Indoor air entering to the dehumidifier will go through the process air section and the material absorbs moisture from the air. Moisture content in the air is decreased, as well as relative humidity. Air entering the reactivation side will be heated up and moisture from the desiccant material will be evaporated to the air. The air is then directed outdoors. See Figure 1.8.

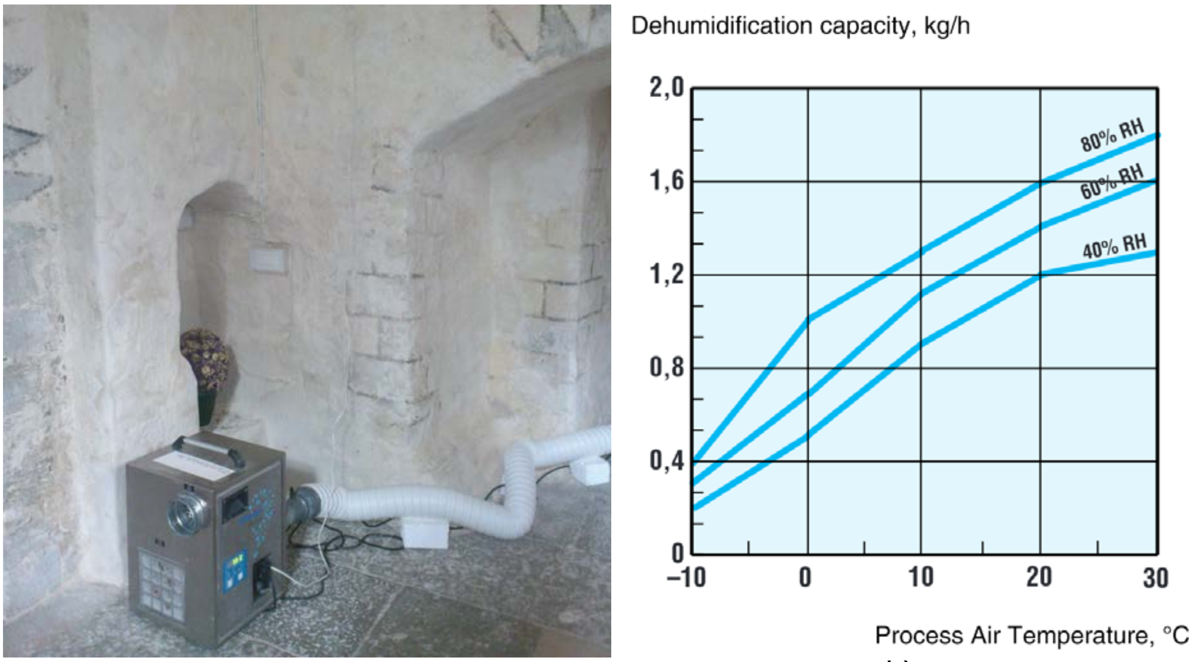
The advantage of the rotary desiccant dehumidifier is that it is more effective in cooler conditions. This is why a rotary desiccant dehumidification was selected.

For dehumidification, two Munters MCS300 rotary desiccant dehumidifiers were used. For the temporary installation, the dehumidifiers were installed in the main room and in the choir room in September 2012 and uninstalled in June 2013. Installation is shown in Figure 1.5. The dehumidifiers worked from September 2012 to December 2012 and from May 2013 to June 2013.

Specification of the Munters MCS300 are presented in Table 8.2:

Table 8.2 Munters MCS300 dehumidifier: technical data

Process air	
Rated airflow (m3/h) Available static pressure (Pa)	300 200
Reactivation air	
Rated airflow (m3/h)	60
Available static pressure (Pa)	200
Power	
Total power (kW)	2.1
115V 1-50/60 Hz (A)	14.5
230V 1–50Hz (A)	9.1
Miscellaneous data	
Operating temperature (°C)	-20…40
Max noise level unducted (dBA)	70
Air filter standard	G3
IEC protective class (unit)	IP44
IPC protective class (electrical panel)	IP54



a) b)

Figure 8.7 a) dehumidifier inside the churchb) dehumidification capacity (Munters, 2010)

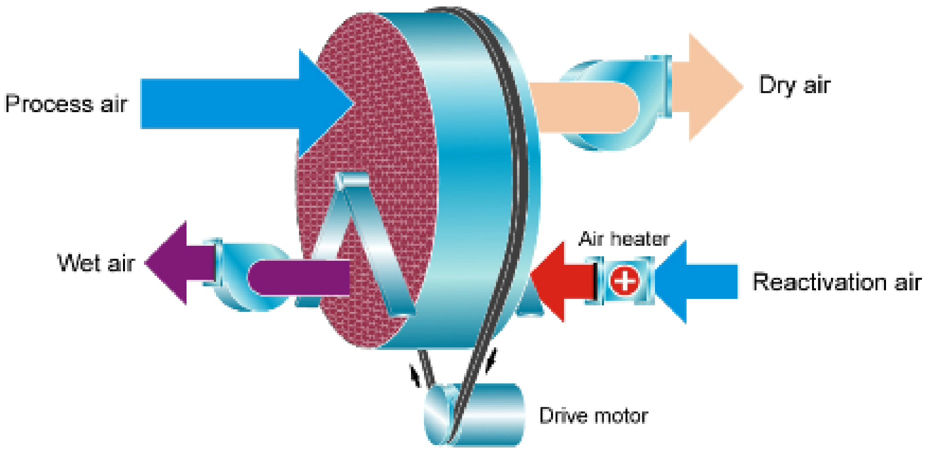


Figure 8.8 Working principle of the dehumidifier (Munters, Munters rotor dehumidification, 2007)

The dehumidifiers were controlled by relative humidity. Two Regin HMH humidistats (hysteresis 3% RH at 45% RH) were used for measuring relative humidity, one for each dehumidifier. The pre-set for RH was 75%. If the indoor relative humidity was higher than the pre-set relative humidity, the system would start; with indoor relative humidity lower than the pre-set, the system would stop.

Two additional HOBO U12 loggers were installed next to the dehumidifiers with a logging interval of 1 minute to calculate the water vapour content of the exhaust air.

Two types of exhaust air ducts were used for the temporary installation of the dehumidifier. For the end of the exhaust pipes, steel spiral ducts were used and installed in the sacristy (Figure 8.9). The dehumidifiers located in the hall and choir room were connected to the steel spiral ducts with flexible PVC ducts. The flexible PVC ducts were used to enable quick and easy decoupling of the pipes to close the sacristy doors if necessary.

a) b)

Figure 8.9 a) ducting in the sacristy b) exhaust pipes exiting the sacristy window

8.2.3 Simulation and calculation

Materials and structures

The structures, materials and their thermal properties are shown in Table 8.3.

Hygric properties of the materials are presented in Table 8.4 and Table 8.5. The first five and the last five layers of the external wall for heat and moisture simulations are render, the middle eight are limestone.

Table 8.3 Structures, materials and their thermal properties

Structure	Material (from inside to outside)	Thickness d, m	Thermal conductivity λ, W / (m·K)	Specific heat J, / (kg·K)	Density …, kg / m^3
Wall	Render	0.025	0.8	790	1800
	Limestone masonry	1.45	1.2	880	2300
	Render	0.025	0.8	790	1800
Sealing	Render	0.025	0.8	790	1800
	Limestone arch	0.4	1.2	880	2300
	Render	0.025	0.8	790	1800
Floor	Limestone slab	0.25	1.2	880	2300
	Soil	1.0	2.0	1000	2000
Door and furniture	Wood	0.05	0.13	1.0	510

Table 8.4 Hygric properties of materials

	Water vapour transmission[1]			Sorption isotherm[2]			
Material	δ_0, m^2/s	B	C	RH_1,%	w_1,kg/m^3	RH_2,%	w_2,kg/m^3
Limestone	1.89×10^{-7}	6.4×10^{-7}	4.7	82	80	100	100
Render	2.929×10^{-6}	3.8×10^{-6}	10	20	57	100	82
Wood	7.3×10^{-7}	2.9×10^{-6}	4.75	84	72	100	100

[1] Water vapour $\delta_v/\Phi = \delta_a + B(RH/100)c$, m^2/s, where δ_0, m^2/s is if RH=0%, B and C are constants and RH, %

[2] Water vapour capacity in relation to relative humidity is given with three lines: start: w=0kg/m3, RH=0%, first breakpoint: w_1; RH_1, second breakpoint: w_2; RH_2=100%

Table 8.5 Division of the exterior wall

	Exterior wall																				
Number of layer	+	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	-	∑ 18
Thickness, mm	+	1	2	5	6	6	6	10	100	614	614	100	10	6	6	6	5	2	1	-	∑ 1500

For the glazing, 1 pane clear glazing was used with a solar factor of 0.85 and heat transmittance of 5.8 W/(m2•K). Window frame was wood (properties shown in Table 8.3). Percentile of the window frame for the glazing was 10%.

Heat losses

For the heat loss calculation, a simple steady-state approach was used. Heat losses for the church were calculated in relation to air-to-air heat pumps. Heat loss formula:

Equation 3

$$H = \sum U_i \cdot A_i + \sum \Psi_j \cdot I_j + \rho_a \cdot c_a \cdot V_{\mathrm{inf}} \qquad \text{W/K}$$

U_i –thermal transmittance of the structure, W/(m^2•K)

A_i – surface area of the structure, m^2

Ψ_j – linear thermal transmittance, W/(m•K)

I_j – length of linear thermal conductivity, m

ρ_a – air density, kg/m^3

c_a – specific heat of air, J/(kg•K)

V_{inf} – average air infiltration, m^3/s

Linear thermal transmittance was calculated using Therm 6 software.

Properties of the used materials are shown in Table 8.3.

The goal of the heat loss calculation was to calculate heat losses in the church and the necessary capacity of the heat pump for heating up the church by 10 °C, enough to reduce relative humidity inside the church to under 70%.

Indoor climate and energy simulations

Since the envelope of the church has a massive heat and moisture capacity, it is essential to use dynamic computer simulation to calculate the church's hygrothermal climate. EQUA's IDA Indoor Climate and Energy 4.2 was used for the computational analysis of indoor climate.

IDA Indoor Climate and Energy (IDA ICE) is a whole-year detailed and dynamic multi-zone simulation application for the study of thermal indoor climate as well as the energy consumption of an entire building. The church model consists of six zones: hall, choir room, sacristy, porch, tower and the attic; see Figure 8.10. The church has one entrance; in the simulation, the front door is always closed. Inner doors connecting the zones are opened. The church has eight windows: four windows in the hall, two windows in the choir room and 2 small windows in the sacristy. All windows are always closed in the simulation. The attic has two half square meter openings in the gable on each side of the roof to replicate the airflow and well-ventilated area under the roof.

In the program, a mathematical model was created of the building where the movement of air, heat and moisture through the external walls and heating, ventilation and humidification is taken into account. In the mathematical model of the hall, four external walls were transformed using the HamWall model (Kurnitski, 2000) for calculating the moisture model. The walls were divided into 18 layers (Table 8.5) to calculate the movement of moisture in the walls. An additional wall part was added to the hall's eastern wall with moisture properties of wood to replicate the wooden parts and structures in the church.

1) Hall
2) Choir room
3) Sacristy
4) Porch
5) Tower
6) Attic

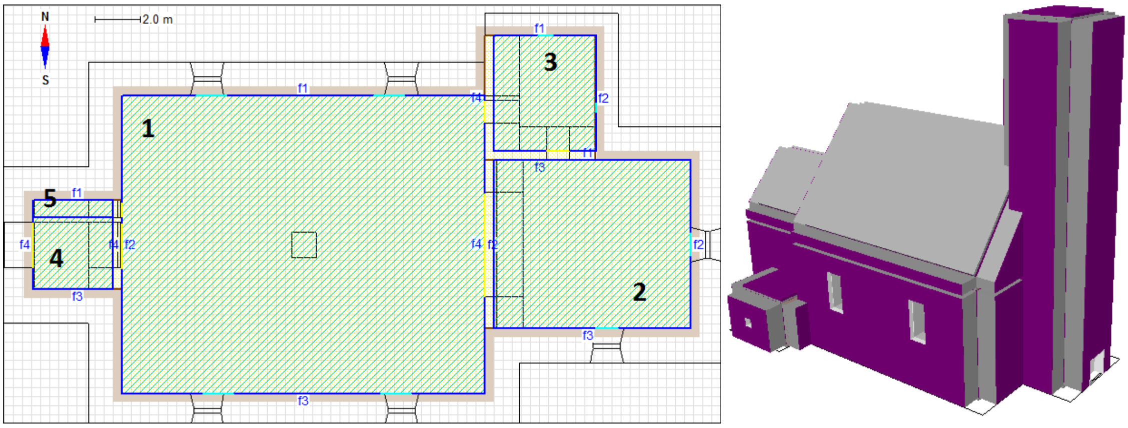


Figure 8.10 Layout of the zones (left). 3D view of the church's simulation model in IDA-ICE software (right).

For the initial calibration of the model, indoor climate data from previous period was used. A second calibration was made using climate data from 2012…2013 for the period where the church was fitted with climate control systems. For both calibrations, separate climate models for outdoor climate were made using local measurements near the church and Estonian Weather Service (EMHI) records from Harku, 40 km from the church.

Climate control principles

For a comparison of indoor climate solutions, the IDA Indoor Climate and Energy simulation models different control principles used.

Adaptive ventilation:

Adaptive ventilation is controlled by excess internal moisture (difference between indoors and outdoors air water vapour content). The air processing unit for adaptive ventilation consist of two ventilators and a heater to heat up the supply air. If the outdoor air vapour content is lower than indoor air's then the system will start up and pump dryer outdoor air indoors. Heating the supply air increases its capacity to adsorb humidity. The scheme of the control system is shown in Figure 8.11.

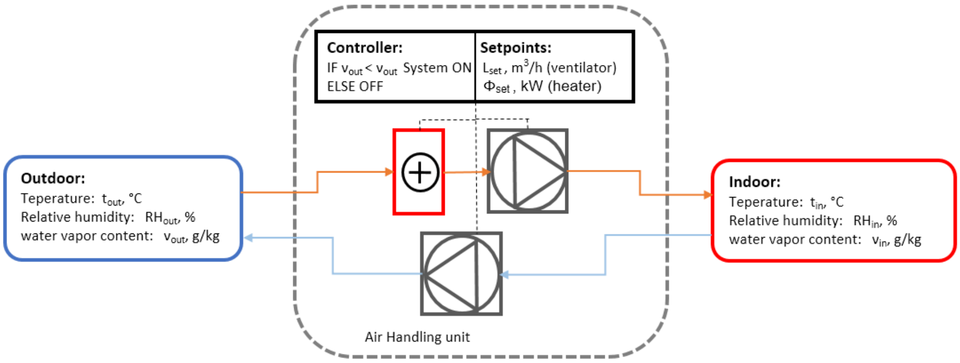


Figure 8.11 Adaptive ventilation control

Conservation heating:

The conservation heating system simulation was controlled by relative humidity. If the indoor RH rose above a specific pre-set, the system started up to heat the indoor air (Figure 8.12).

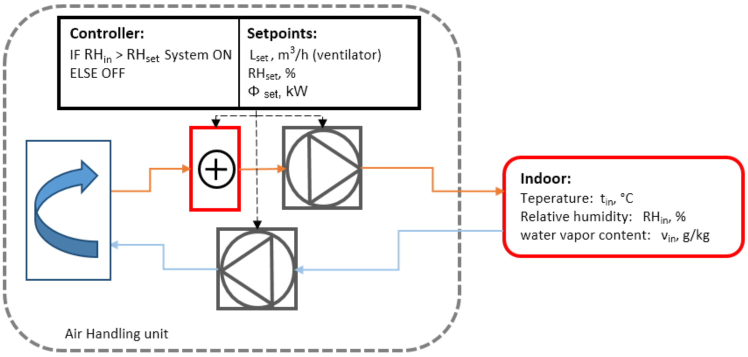


Figure 8.12 Conservation heating control

For the heating simulation, direct heating was used. For energy consumption, the heat pump energy consumption was calculated from direct heating simulation using the Coefficient of Performance given in the heat pumps manual.

Dehumidification:

For the simulation of dehumidification, a condensation dehumidifier is used (Figure 8.13). Vapour content is removed from inside air and then heated to indoor temperature. Dehumidification is controlled by relative humidity.

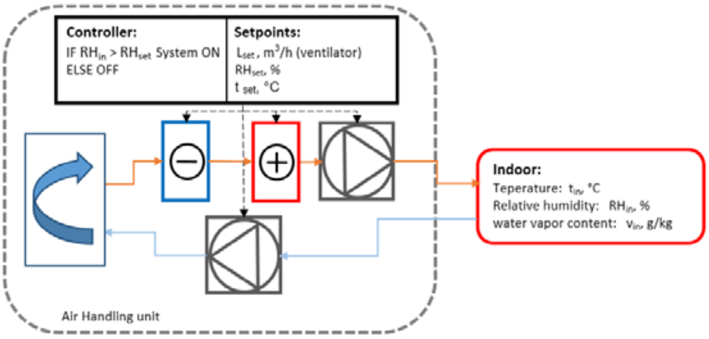


Figure 8.13 Dehumidification control

8.1 Results

8.1.1 Measurements

Indoor temperature and humidity conditions

Indoor climate measurements show high relative humidity throughout the year. For the measurement period, average relative humidity throughout the year on the balcony was 87% and near the altar, 90%.

Temperature fluctuation is slow, under 1 °C/h and not very dependent on outdoor temperature. The twenty-four hour average temperature and relative humidity trend is shown in Figure 8.14. In the first period, temperature was below 0 °C 14% of the time. The lowest measured temperature was -2.7 °C on the balcony in February and the highest temperature, 20.2 °C in July, also on the balcony. Monthly average indoor temperatures in the first measurement period were between -1.5...17.1 °C. For indoor relative humidity, the monthly averages were between 70…97%.

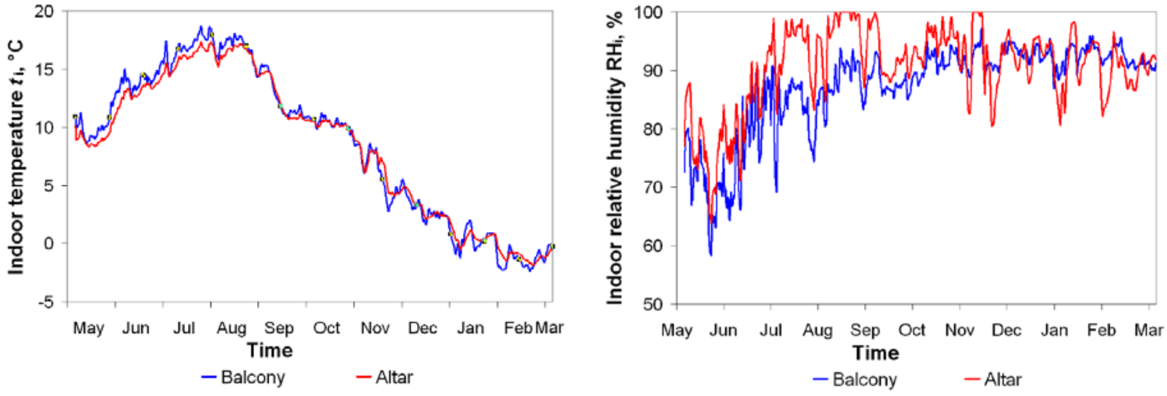


Figure 8.14 Daily average temperature (left) and relative humidity (right) in the church

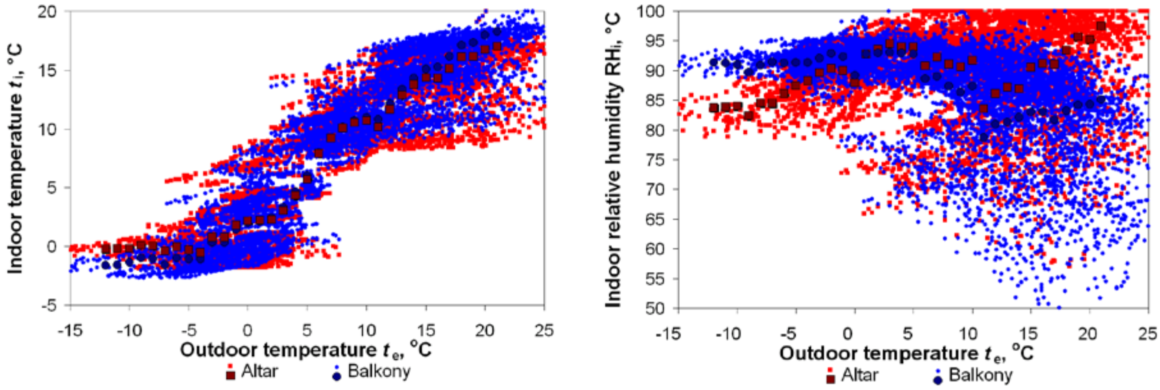


Figure 8.15 Indoor temperature (left) and relative humidity (right) in relation to outdoor temperature

Monthly average indoor temperature, relative humidity and air moisture content on the balcony and near the altar is shown in Table 8.6.

Table 8.6 Monthly indoor climate in the Church of the Holy Cross

	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
	Temperature, °C										
Balcony	10.0	13.8	16.2	17.1	12.7	10.4	6.3	3.1	0.4	-1.5	-0.7
Altar	9.1	12.8	15.8	16.5	12.6	10.3	6.7	3.2	0.6	-1.2	-0.9
	Relative humidity, %										
Balcony	70	76	84	88	88	91	92	93	93	92	91
Altar	76	82	94	97	92	95	92	93	91	90	91
	Water vapour content, g/m^3										
Balcony	6.6	9.0	11.9	12.8	9.8	8.8	6.8	5.6	4.6	4.0	4.2
Altar	6.7	9.2	12.6	13.6	10.2	9.1	7.0	5.6	4.6	4.0	4.1

Indoor humidity depends on the outdoor climate and with the rise of outdoor water vapour content, indoor humidity increases. Indoor humidity is higher than outdoor humidity most of the time, see Figure 8.16.

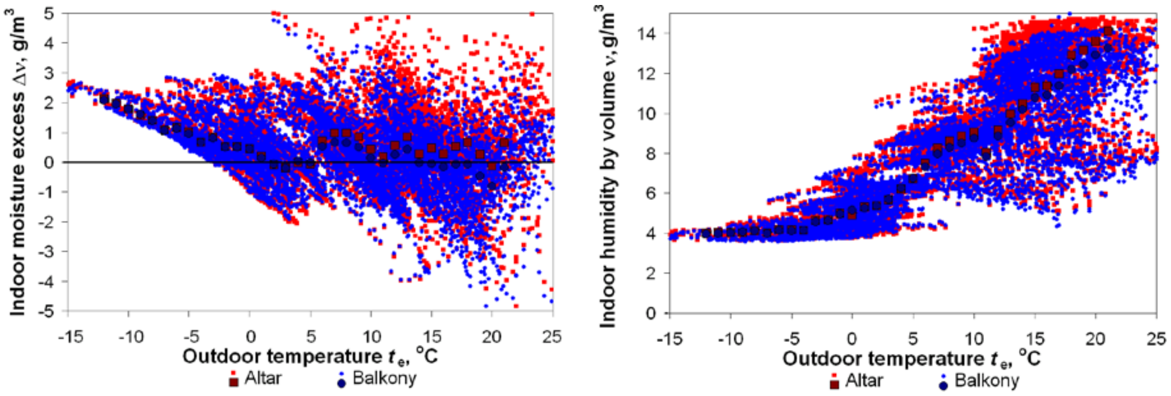


Figure 8.16 Indoor moisture excess and indoor humidity by volume

Air infiltration

Infiltration measurements were conducted using the passive tracer gas technique.

The primary results of the measurements yield the time-averages of the local mean ages of air at the positions where the air samplers have been placed (Figure 8.2). The local mean age of air is a measure of how long the air around the measurement point has stayed inside the building on average. The average mean age of air is the best approximation of the mean air exiting the church and can thus be used to estimate the total infiltration of the church (Table 8.7).

The difference in measurements conducted in May and March can be explained by the average value of the difference between outdoor and indoor temperature being around 3 °C lower in the church during the second measurement period.

Table 8.7 Air infiltration measurements using the passive tracer gas technique

Room	Volume m^3	Age of air τ, h	ACH, h^{-1}	Q, m^3/h
		18.04.…18.05 (t_e: 8.4 °C , t_i: 7.1 °C)		
Whole church	2330	1.64	0.61 ± 0.02	1423
Hall	1675	1.69	0.59 ± 0.14	-
Choir room	550	1.52	0.66 ± 0.06	-
Sacristy	65	1.22	0,82 ± 0.08	-
		17.03…18.04 (t_e: 2.0 °C, t_i: -0.31 °C)		
Whole church	2330	3.84	0.26 ± 0.01	607
Hall	1675	3.75	0.27 ± 0.02	-
Choir room	550	5.37	0.26 ± 0.02	-
Sacristy	65	5.18	0.19 ± 0.02	-
		20.02…19.03 (t_e: -5.9 °C, t_i: 0.7 °C)		
Whole church	2330	3.02	0.33 ± 0.27	798
Hall	1675	2.81	0.36 ± 0.27	-
Choir room	550	2.75	0.36 ± 0.25	-
Sacristy	65	2.77	0.36 ± 0.28	-

Dehumidification and conservation heating

Climate controlled dehumidifiers and air-to-air heat pumps were used. The system was installed in September 2013. The dehumidifier and heat pump were tested separately throughout the test period.

Main climate test periods in the church with air-to-air heat pump and dehumidification: (Figure 8.17, Figure 8.18)

- Period 1 (DEHUM): 14 September 2012, installation of the dehumidifier. Pre-set for the dehumidification controller is set to 75% RH. Dehumidification works until 4 December 2012.
- Period 2 (HP): Air-to-air heat pump is started up using relative humidity control with a pre-set of 75% RH.
- Period 3 (HP (No RH)): Heat pump is set to work using temperature control to heat up the church for the restorers (relative humidity control is turned off). Heat pump is switched off on 30 May 2013.
- Period 4 (System OFF): Climate control systems are turned off in the church and the climate is allowed to return to natural balance.

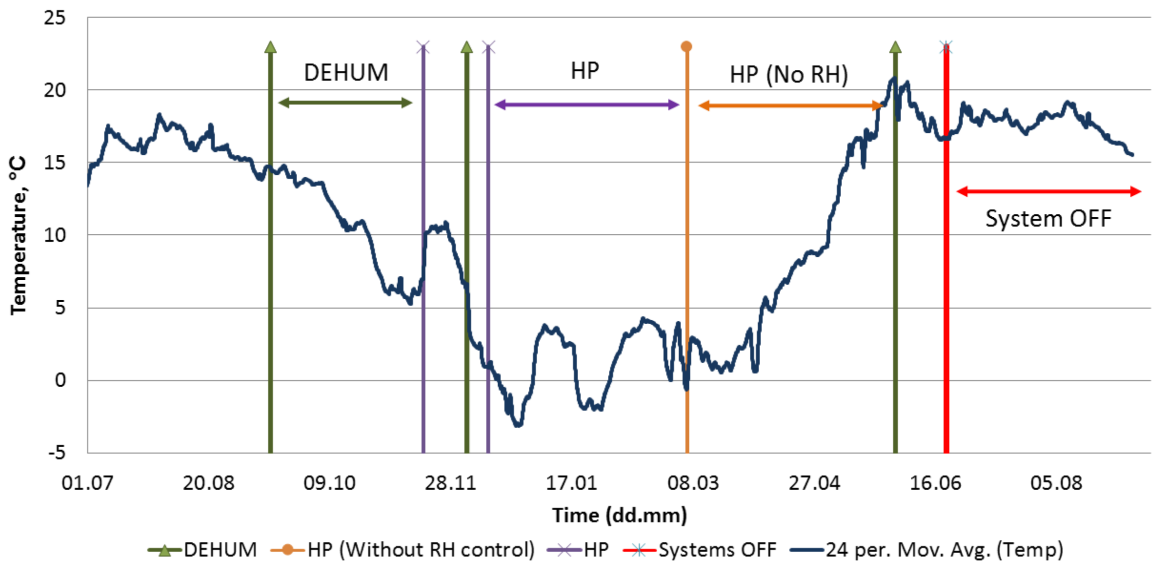


Figure 8.17 Temperature (24h average) in the climate control period

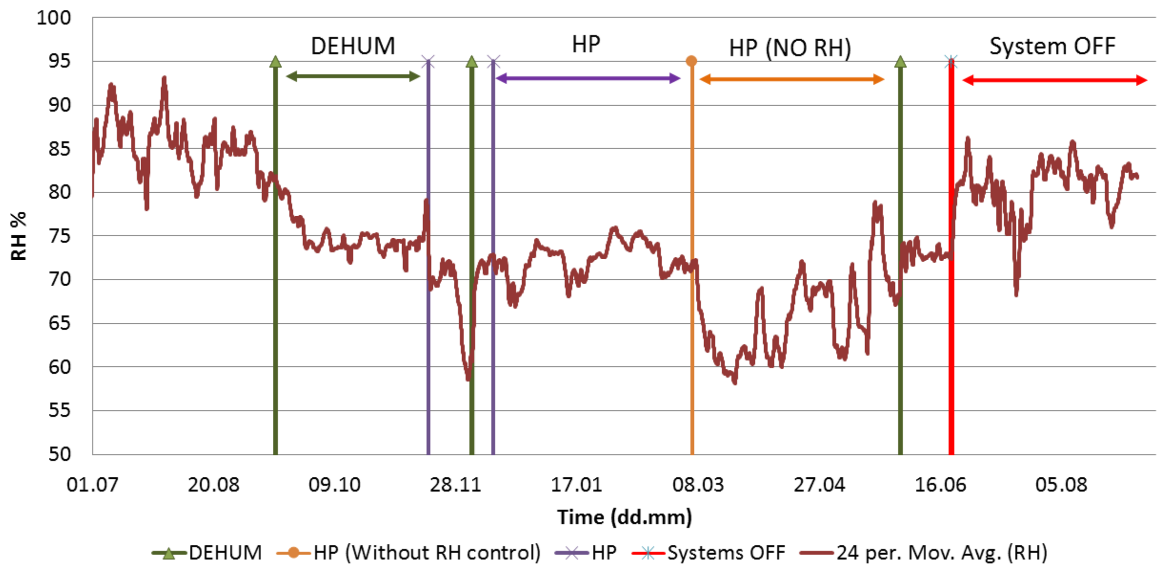


Figure 8.18 Relative humidity (24h average) in the climate control period

Both dehumidification and the air-to-air heat pump reduced the relative humidity level in the church hall. In different locations (altar, organ and sacristy), relative humidity tends to be a bit higher than in the hall. (Figure 8.19, Figure 8.20, Figure 8.21, Figure 8.22)

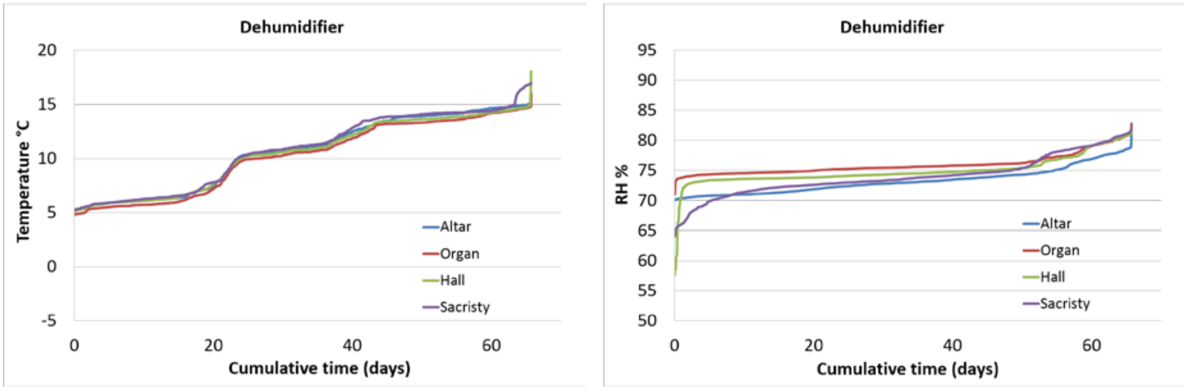


Figure 8.19 Temperature (left) and relative humidity (right) in different locations using the dehumidifier (period: 14.09.2012…16.11.2012, te: -7.5…19.2 °C)

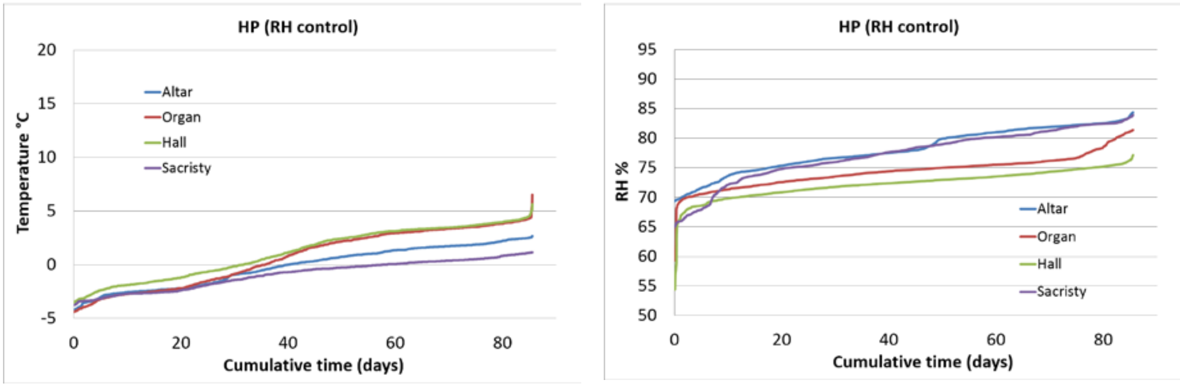


Figure 8.20 Temperature (left) and relative humidity (right) in different locations with conservation heating controlled by relative humidity (period: 13.12.2012…05.03.2013, te: -19.2… 6.9 °C).

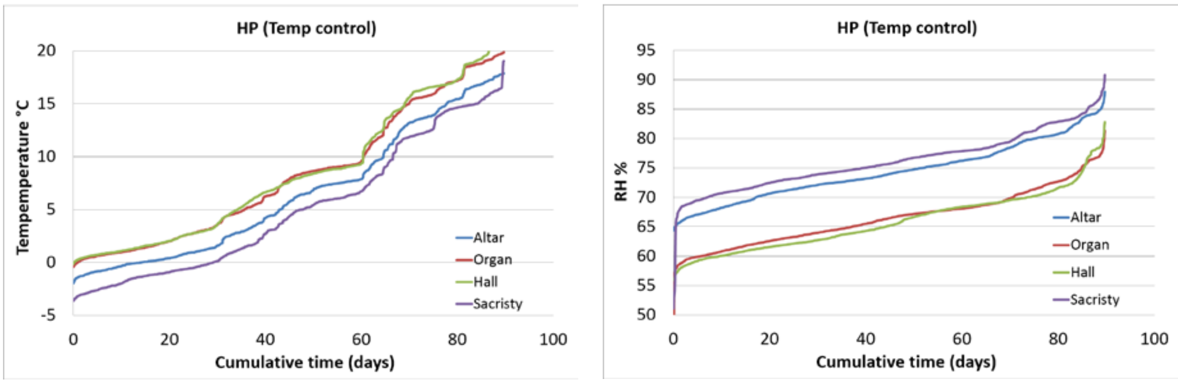


Figure 8.21 Temperature (left) and relative humidity (right) in different locations with conservation heating controlled by temperature (period: 5.03.2013…20.05.2013, te: -22.4…27.9 °C).

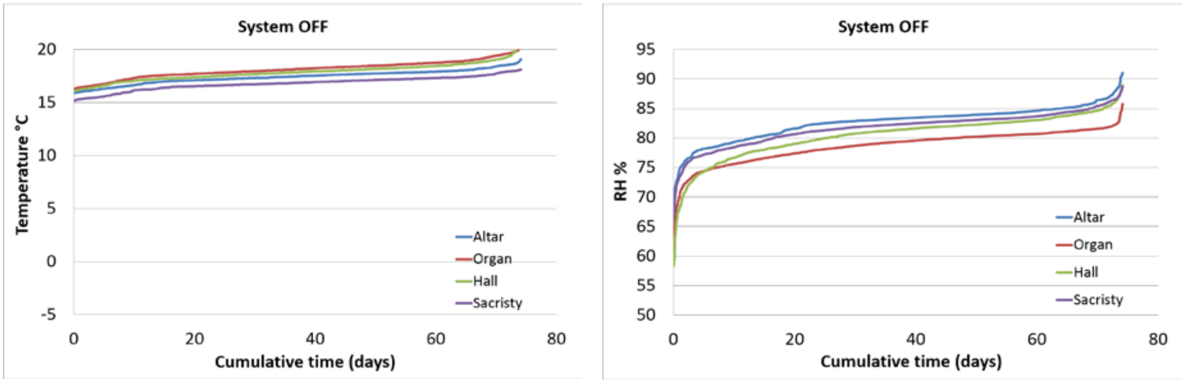


Figure 8.22 Temperature (left) and relative humidity (right) in different locations without climate control (period: 20.06.2013…30.08.2013, te: 6.8…33.0 °C)

In the figures above (Figure 8.19, Figure 8.20, Figure 8.21, Figure 8.22), the values are sorted from lowest to highest to illustrate the overall temperature and relative humidity in different locations in the church. The values have been measured in different outdoor climatic conditions. Different low peaks of temperature and high peaks of relative humidity appear because of the insufficient installation power of the systems.

With dehumidification, temperature throughout the church is almost the same and relative humidity is also quite similar. With the controls turning the system on when relative humidity was higher than 75% and off at 70%, the system has kept relative humidity between 70…75%. The similarity results from the locations of the dehumidifiers. The dehumidifiers create sufficient airflow throughout the church to decrease the overall relative humidity in all rooms. (Figure 8.19)

With the air-to-air heat pump controlled with relative humidity, the controller pre-set was alternated between 60…75% throughout the period. The higher temperature and therefore lower relative humidity in the hall and next to the organ (Figure 8.20) result from the location of the heat pump. With the heat pump and controller located in the hall, relative humidity is kept within the permitted range. However, relative humidity in other rooms tends to be higher than in the hall and the controller's pre-set; this is caused by the heat pump's low airflow that does not transfer heat to the choir and sacristy to reduce relative humidity. The same phenomenon occurs with an air-to-air heat pump with temperature control. (Figure 8.21)

With both systems off, temperature and relative humidity throughout the church stabilize (Figure 8.22). The higher temperature and slightly lower relative humidity in the hall and next to the organ result from the bigger windows in the southern facade and higher solar radiation in July.

8.1.2 Simulations and calculations

Heat loss

Material properties for the heat loss calculations are shown in the Table 8.8.

Table 8.8 Material properties and heat loss in the church

Construction (thickness, m)	Area, m^2	Thermal transmittance U, $W/(m^2 \cdot K)$	Heat loss H, W/K
Floor	280	0.26	72.8
Ceiling	339	2.8	949
Windows	25	5.8	145
Hall walls (1.5)	237	0.7	166
Walls (1,9)	62	0.6	37.2
Porch walls (0,6)	27	1.4	37.8
Door	3.8	1.1	4.18
Total			1411

In the calculation of heat losses, some of the external walls of the church are given with different thicknesses.

Table 8.9 Cold bridges and heat losses in the church

Thermal bridges	Length m	Linear thermal transmittance Ψ_j, W/(m·K)	Heat loss H, W/K
Hall wall-wall	25	0.20	10.4
Sacristy wall-wall	6	0.47	2.8
Porch wall-wall	10	0.75	7.5
Window-wall	77	2.01	154.4
Floor-wall	76	0.44	33.3
Ceiling-wall	46	0.40	18.5

For infiltration, an average of the three measurements was taken, leaving the total heat losses of the church 1740 W/K

Calibration of the indoor climate and energy simulation model

For computer simulations, IDA Indoor Energy and Climate was used and a mathematical model created to calculate a dynamic simulation of heat, air and moisture.

Due to the desire to control the church's indoor climate and mainly reduce the relative humidity inside the church, different scenarios have been calculated with different systems to determine the efficiency of each climate control system and also assess the energy consumption of each solution.

The indoor climate and energy simulation model was calibrated with measurements during two periods:

- non-climate controlled (unheated and not dehumidified) climate in the church: during the first period;
- climate controlled (conservation heating, dehumidified) climate in the church: during 2012…2013;

The correlation in calculated and measured temperature and humidity in the unheated period is satisfactory. The main difference may be the bigger daily fluctuations of the measured temperature and water vapour content.

For calculations for the heated period, the water vapour content is satisfactory (Figure 8.24). There are bigger variations in temperature. Lower temperatures in the simulation in March and April are caused by the fact that in this simulation, the system was controlled by relative humidity but in the church the heat pumps were controlled by relative humidity (Figure 8.24). Large fluctuations in relative humidity are caused by the bigger temperature differences (Figure 8.25).

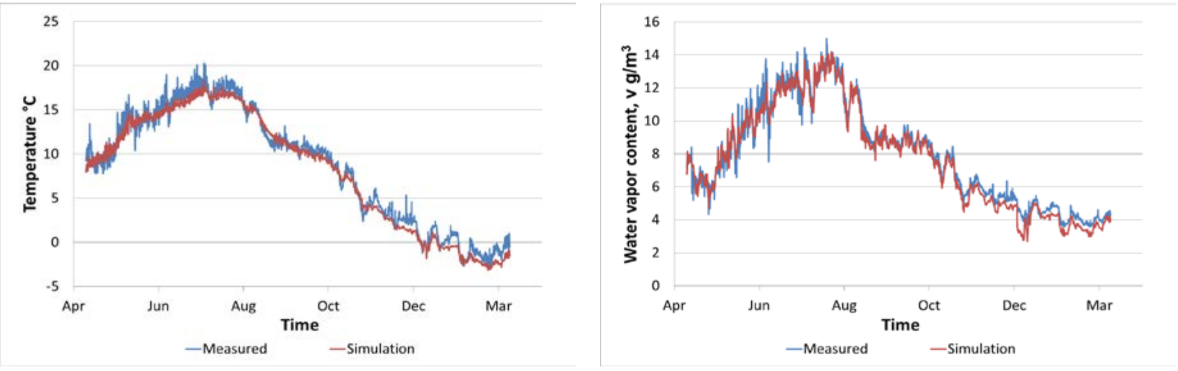


Figure 8.23 Comparison of measured and calculated temperature (left), water vapour content (right) in a non-climate controlled church

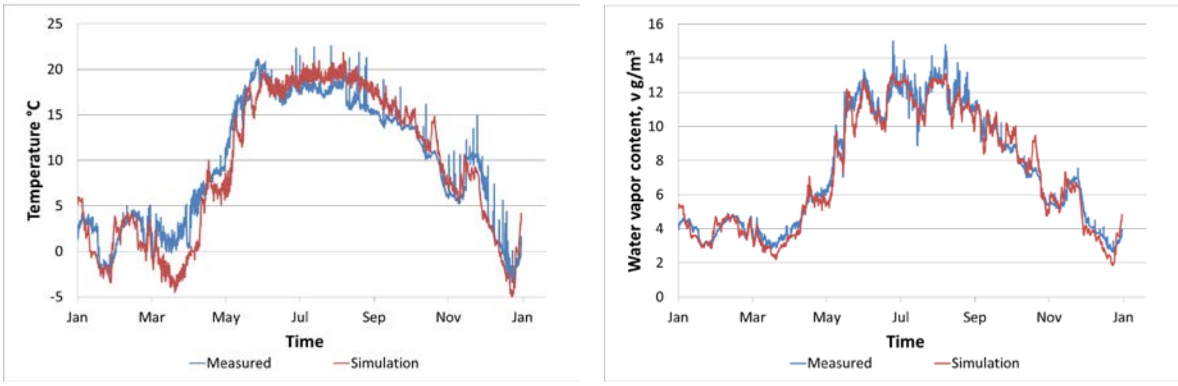


Figure 8.24 Comparison of measured and calculated temperature (left), water vapour content (right) in a climate controlled church

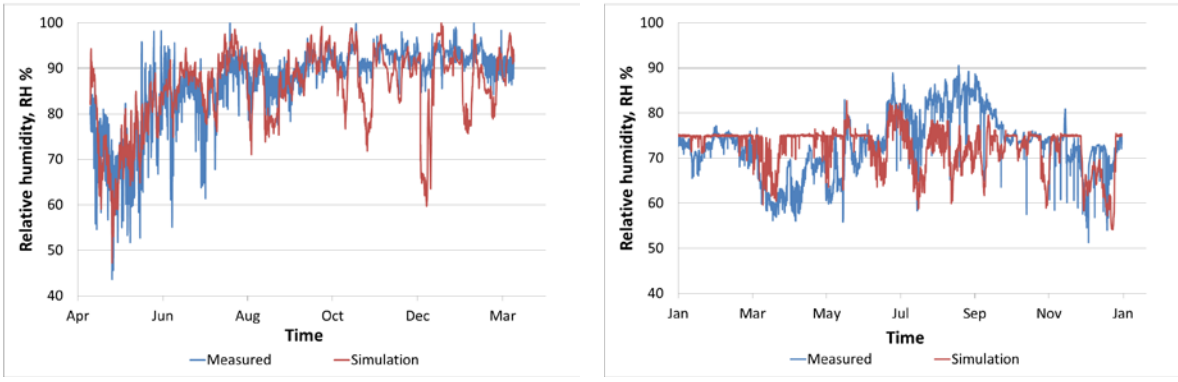


Figure 8.25 Comparison of measured and calculated RH in a non-climate controlled church (left) and a climate controlled church (right)

Performance of adaptive ventilation

With lower water vapour content outside than indoors, the ventilation system is turned on to deliver dryer air inside. In the adaptive ventilation simulation, different airflows as well different heating capacities were simulated to determine the most efficient solution.

In the adaptive ventilation simulation, the inlet air temperature was limited to 25 °C to avoid to high inlet temperatures and excessive dryness of the air net to inlet vent.

The higher the heating power, the more efficient adaptive ventilation is, with the maximum tested heating power of 30 W/m^2 the simulation showing the most effective drying in the church (Figure 8.26, left). Different airflows also create differences. With bigger airflows, the air speed increases so that heat transfer from the heater to the inlet air decreases. With very low air flows, the air flows are not sufficient to ensure lower relative humidity rates. The most efficient airflows are around 200…500 l/s (Figure 8.26, left), decreasing relative humidity inside the church the most.

The systems with the highest energy consumption are the ones with higher heating power as the heater needs more energy. The most efficient airflows are also the most energy consuming (Figure 8.26, right). With a heating power of 30 W/m^2, the most power consuming airflow rate is 500 l/s, the most efficient is 300 l/s with relative humidity under 70% for 46.5% of the year.

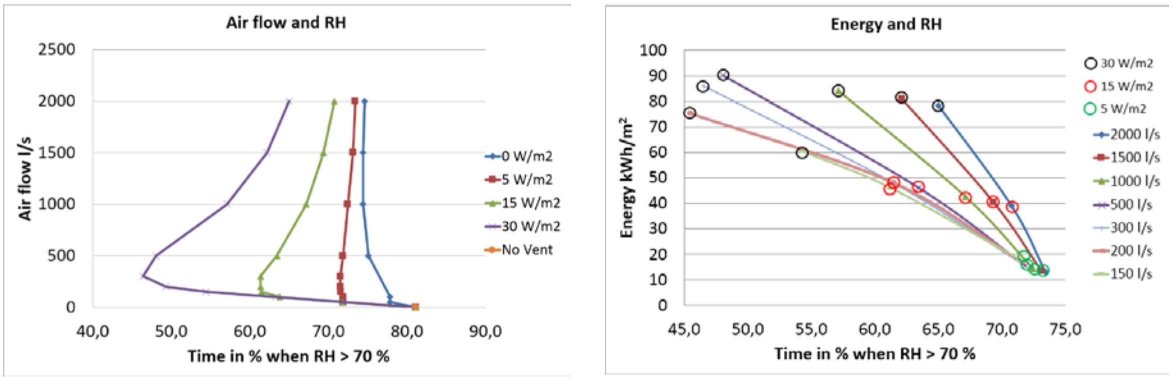


Figure 8.26 Left: Efficiency of adaptive ventilation with different airflows and heating powers. Right: Energy use of adaptive ventilation per year with different air flows and heating

Performance of conservation heating

In the simulation, the conservation heating system is controlled by relative humidity, so that the system would decrease indoor relative humidity to a certain level. The heating system decreases relative humidity by increasing the indoor temperature and increasing the capability of the air to hold more water vapour.

When reducing the relative humidity by heating up the air in the church, indoor air temperature would increase. In the autumn, winter and spring it would increase the indoor thermal comfort in the church, in the summer period the heating could increase too much.

With lower pre-sets for relative humidity, the heating system's work load increases and so will indoor temperature. Figure 8.27 shows the temperature increase in the church with conservation heating with relative humidity pre-sets of 50% and 70% and also the conditions inside the church with no conservation heating. The annual average temperature increase in the church with conservation heating and a pre-set of 70% is 2.7 °C and with a pre-set of 50%, 7.3 °C.

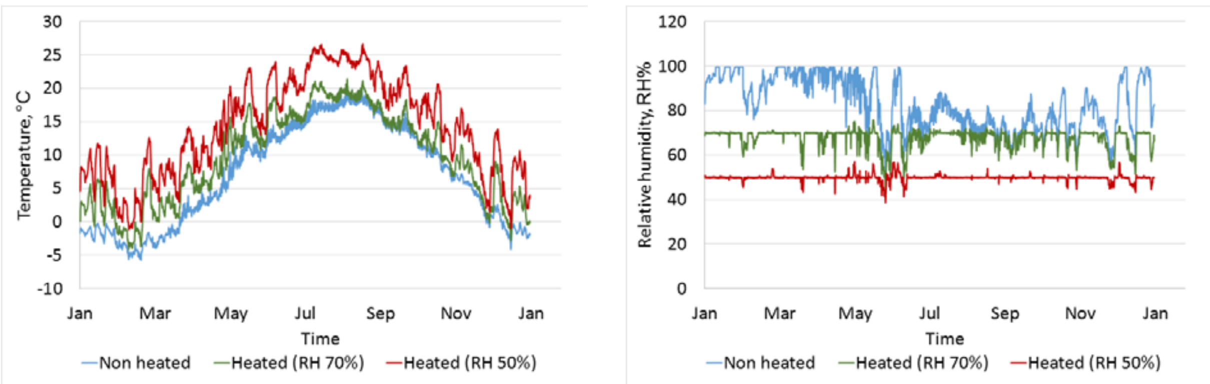


Figure 8.27 Temperature (left) and relative humidity (right) in the church with different relative humidity pre-sets for heating. (Simulation based on the Estonian energy calculation base year)

Performance of dehumidification

Dehumidification is controlled by relative humidity. With relative humidity increasing above the given pre-set, the system starts up and decreases relative humidity.

In the simulation, a condensation dehumidifier was simulated because of the absence of the rotary dehumidifier option in the simulation program.

The dehumidifier decreases relative humidity by absorbing water vapour from the air. With dehumidification, there is practically no change in indoor temperature in the church.

Comparison of climate solution

Using different simulations for adaptive ventilation, heating, heat pump and dehumidification, the energy consumption of different systems was calculated. The energy consumption of the systems is calculated using the Estonian energy calculation base year designed for calculating indoor climate and energy usage in buildings. Climate data is based on measurements from 1970 to 2000 and based on the Estonian standard EVS-EN ISO 15927-4:2005

Unlike conservation heating and dehumidification, adaptive ventilation does not guarantee stable indoor relative humidity because the system is less controllable. Figure 8.28 shows a comparison of relative humidity with conservation heating and adaptive ventilation. Adaptive ventilation is shown without heating and with heating. Adaptive ventilation with heating uses 30W/m^2 heating power and an airflow rate of 300 l/s, determined to be the most efficient (Figure 8.26).

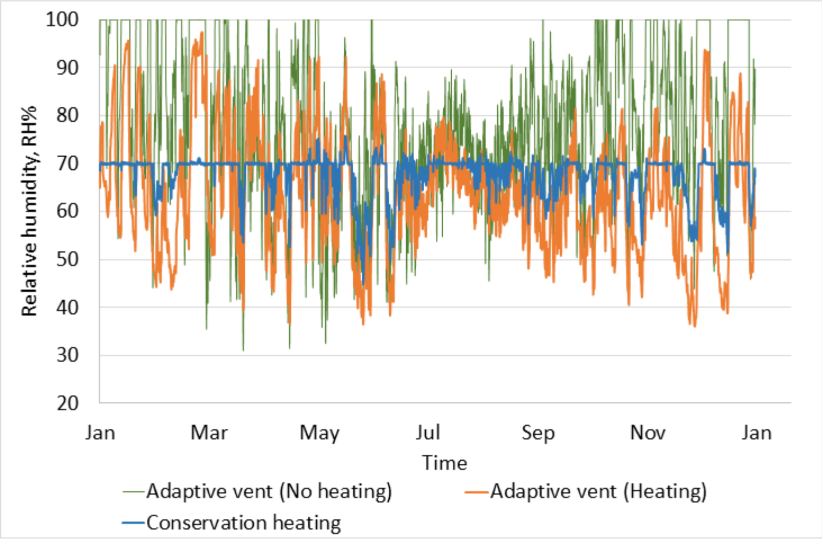


Figure 8.28 Comparison of indoor relative humidity for adaptive ventilation and conservation heating

Figure 8.29 shows a comparison of the annual energy consumption of conservation heating with direct heating and a heat pump as well as dehumidification for ensuring different values of indoor relative humidity. The air-to-air heat pump is the most energy efficient with an energy consumption of 34.6 kWh/m^2 per year to ensure a relative humidity of 70%. Rotary dehumidification is more energy consuming with an energy consumption of 57.5 kWh/m^2 per year to ensure the same 70% relative humidity. Although for ensuring lower relative humidity than 56%, the rotary dehumidifier is more energy efficient then a heat pump. The most energy consuming is direct heating with an energy consumption of 84.9 kWh/m^2 per year to ensure a relative humidity of 70%. Dehumidification is more energy consuming than direct heating only at higher relative humidity, 85…90%.

The most energy consuming is adaptive ventilation. This is due to the fact that with adaptive ventilation, you have to heat up the outside air while conservation heating will heat up the air indoors. With adaptive ventilation, relative humidity indoors is not that controllable so that in the energy consumption calculation, the 90% percentile is taken from the relative humidity to eliminate the high peaks of indoor relative humidity.

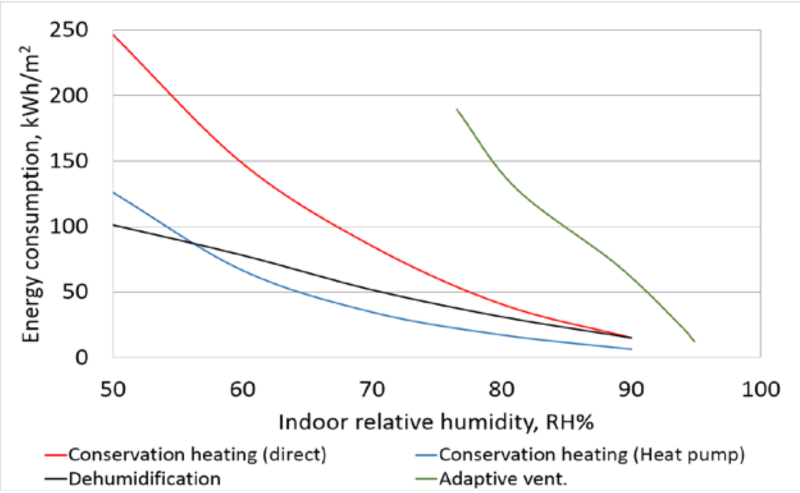


Figure 8.29 Comparison of conservation heating, dehumidification and adaptive ventilation

8.2 Conclusion

In Estonia, most medieval churches have no heating or any other climate control systems installed; indoor climate is thus mainly determined by the outdoor climate. Because of the churches' massive limestone walls, the large moisture capacity and lower thermal resistance of these structures, it is possible for indoor climate to have high relative humidity and the inner surfaces to have a temperature below the dew point. This results in water condensation on the inside surfaces of the structure. Higher relative humidity can increase the risk of mould growth and abscess.

Establishing a suitable indoor climate in old churches is a complex task. The conservation of culturally valuable constructions and details must be taken into consideration. The most important indicator of thermal comfort for people is temperature; however, for the cultural treasures, the most important physical indicator is relative humidity. The higher limit of humidity is determined by the growth of mould and abscess and condensation on walls and on windows; the organ is also affected more by relative humidity than by ambient temperature.

The indoor climate of a majority of Estonian medieval churches without climate control is too humid; therefore, a demand exists for climate control systems to ensure better conservation of the artworks and structures of the churches.

8.2.1 Indoor climate

Measurements conducted during the first period show high relative humidity. Average relative humidity throughout the year during the measurement period was 87% on the balcony and 90% near the altar. Temperature fluctuations are slow and not very dependent on outdoor temperature. The lowest measured temperature was -2.7 °C on the balcony in February and the highest temperature was 20.2 °C in July, also on the balcony.

In the climate control system test period where dehumidification and air-to-air heat pumps were used, relative humidity immediately decreased while the systems were operating.

Because the dehumidification devices were installed separately in different locations in the church and with better airflow distribution, the dehumidifiers could maintain the desired parameters better throughout the church. With the system pre-set to 75%, relative humidity was 70…75% everywhere throughout the church.

With an air-to-air heat pump, relative humidity in the hall is kept inside the permitted and desired limits but in the choir room and in the sacristy, it was higher than in the hall, this because both indoor units were installed in the hall and the airflow was insufficient to increase the temperature. As a result, relative humidity was also higher. It is easy to see that when the systems are turned off, the relative humidity increases to above 75…80%.

8.2.2 Energy use

Unlike conservation heating and dehumidification, adaptive ventilation does not guarantee stable relative humidity indoors because the system is less controllable. Achieving a certain pre-set for indoor relative humidity is not possible using adaptive ventilation.

The most energy efficient of all climate control measures is conservation heating with an air-to-air heat pump, with an energy consumption of 23 kWh/m^2 per year to ensure a relative humidity of 70%. The energy consumption of rotary dehumidification is 58 kWh/m^2 per year to ensure the same 70% indoor relative humidity. The most energy consuming is direct heating with an energy consumption of 85 kWh/m^2 per year to ensure a relative humidity of 70% indoors. Dehumidification is about as energy consuming as direct heating at higher relative humidity, 85…90%. Adaptive ventilation with direct heating is the most energy consuming. This is due to the fact that with adaptive ventilation, you have to heat up the outside air while conservation heating heats up only indoor air.

8.3 Acknowledgements

The authors are grateful to Endrik Arumägi, Üllar Alev, Indrek Raide, Kalle Kuusk, Jevgeni Fadejev from Tallinn University of Technology for the help with measurements and simulations.

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9 SOLUTIONS FOR SUSTAINABLE MAINTENANCE AND CONSERVATION OF HISTORIC CHURCHES

Poul Klenz Larsen, Magnus Wessberg, Tor Broström

9.1 Introduction

There are 92 medieval churches on Gotland. They are located in rural areas, where the population has gradually diminished during the last century. Typically the churches are used for services or other activities around once a month. The majority of the rural churches are around 800 years of age. They are characterized by solid lime stone walls with lime plaster. Some have wooden ceilings, others stone vaults. Compared to more recent structures, these buildings have large thermal inertia and poor thermal insulation. As energy prices are increasing it is not possible to keep them permanently heated and as a consequence moisture problem have increased; mostly mould growth and insect damages. More than 20 Gotland churches have been monitored after reports of visible mould growth and bad smell. Clearly there is a need for cost efficient and robust climate control systems.

This chapter gives an overview of different control strategies that have been implemented in Gotland churches. To broaden the empirical background, results from some similar Danish case studies have been included.

The text is based on scientific papers that have been or will be published within the framework of the SMC project.

Larsen P.K., Broström T. 2012. *Climate control strategies for occasionally used churches. Heat, dehumidify, ventilate – or do nothing*. In: Elin Dahlin (ed.) Proceedings on the 2nd European Workshop on Cultural Heritage Preservation, Kjeller, Norway 24th–26th September 2012 pp124 – 130

Larsen P.K., Wessberg M., Broström T. 2013. *Adaptive ventilation for occasionally used churches.* Proceedings of the 3rd European Workshop on Cultural Heritage Preservation, Bolzano, September 2013 pp. 55-62.

Wessberg M., Larsen P.K., Broström T. *Solar energy augmented adaptive ventilation in historic buildings*. (Submitted for publication to the 10th Nordic Symposium on Building Physics, 2014.

9.2 Conservation heating

Conservation heating is the concept of heating a building in order to keep a constant relative humidity. The temperature is continuously adjusted and not controlled to a constant set point. Conservation heating has been used for many years to maintain a medium relative humidity (RH) in historic houses (Stanisforth et al). It is a simple and robust climate control strategy, but the stability of RH depends on the air infiltration rate and the temperature control. A leaky church with high thermal stability will experience large variations in RH. A problematic aspect of conservations heating is that it is sometimes required to heat in summer in order to keep the RH at an acceptable medium level. This may cause uncomfortably high temperatures and high energy consumption (Larsen 2007).

Another generic problem with conservation heating is the positive feedback mechanism, where heating promotes evaporation from the building thus increasing the water vapor content of the air. The total effect of heating is lower relative humidity, but the increased absolute humidity can be problematic.

Conservation heating can be implemented in any church with permanent or temporary heating installations. Direct electric heaters are frequently used because they need little installation work. Central heating is more invasive due to the piping, but allows for the use of different heat sources.

In most cases an existing heating system can be reused, but a new control system may be needed. The energy consumption for conservation heating is high, because the heat loss from historic churches is large due to poor thermal insulation. In a case study on three historic buildings owned by National Trust, the annual energy consumption for heating was 39 – 53 kWh/m^3 (Blades et al).

But the energy need can be significantly reduced by the use of heat pumps. Heat pumps are particularly well suited for conservation heating, because they perform better with a small temperature difference between inside and outside (Brostrom 2008). The challenge is how to integrate the heat pump in the church. Ground heat combined with floor heating is very good from a technical point of view, but may involve archaeological excavations, both inside and outside the church. Air to air heat pumps may be difficult to adapt to the interior and exterior of the church.

Air to air heat pumps have been installed in two Gotland churches, Garda and När, see fig 1 and 2. The installation in Garda church has been successful in providing conservation heating with a significantly reduced energy demand. The heat pump is controlled with respect to relative humidity and mould risk has been eliminated.

For most air-to-air heat pumps it is necessary to maintain a minimum temperature, typically 8-10 °C, to ensure that the defrosting function works. In När church, the heat pump was undersized and did not have enough power to maintain the minimum temperature. As a consequence operation was disrupted due to icing, se fig 2.

Figure 9.1 An air – to - air heat pump with the heating unit integrated in the furniture and the outside unit. Garda church, Gotland, Sweden

Figure 9.2 An air – to - air heat pump installation. När church, Gotland, Sweden

9.3 Dehumidification

9.3.1 Introduction

Dehumidification can be used either permanently or seasonally to control the RH inside the church. The methods and the devices have been used for decades by the industry and by private or public buildings owners to control the RH in damp environments. Within recent years dehumidification has been adapted for energy efficient climate control in heritage buildings in Denmark (Larsen & Brostrom 2011). The annual energy consumption ranges from 1 – 20 kWh/m^3, depending on the infiltration rate and the internal sources of moisture.

There are two methods for dehumidification: Condensation and sorption. The sorption dehumidifier passes the air through a desiccant, usually silica gel, which absorbs the water vapour from the air. When the desiccant is full, a flow of warm air releases the moisture to the outside. A sorption dehumidifier needs ducts to distribute the dry air, which may be difficult to fit into a church. The sorption dehumidifier works at low temperatures, even below zero degrees. This method is favorable in churches with little or no heat in the winter.

The condensing dehumidifier contains a heat pump with a compressor, a heating element and a cooling element. A fan draws air over the cooling element to condense the moisture, which is collected in a bucket or led to a drain. The cooled air then passes through the heating unit, warming with heat from the compressor. The condensing dehumidifier is not efficient below 8 ˚C, because ice is generated on the cooling unit, so intermittent defrosting is required. This method is appropriate for churches with some basic heating or when the high RH levels occur mainly in the summer.

9.3.2 Case study – Näs church

Näs church is a sandstone building located on the southeastern part of Gotland. It is heated intermittently, between services there is no heating at all. The church had for years been known to be very damp and problems with bad smells were increasing. In order to quickly dry out the church, a large sorption dehumidifier was installed (Figure 9.3). The humidifier was controlled with respect to RH.

Figure 9.3 An sorption dehumidifier installed in Näs Church, Gotland, Sweden. The installation is temporary.

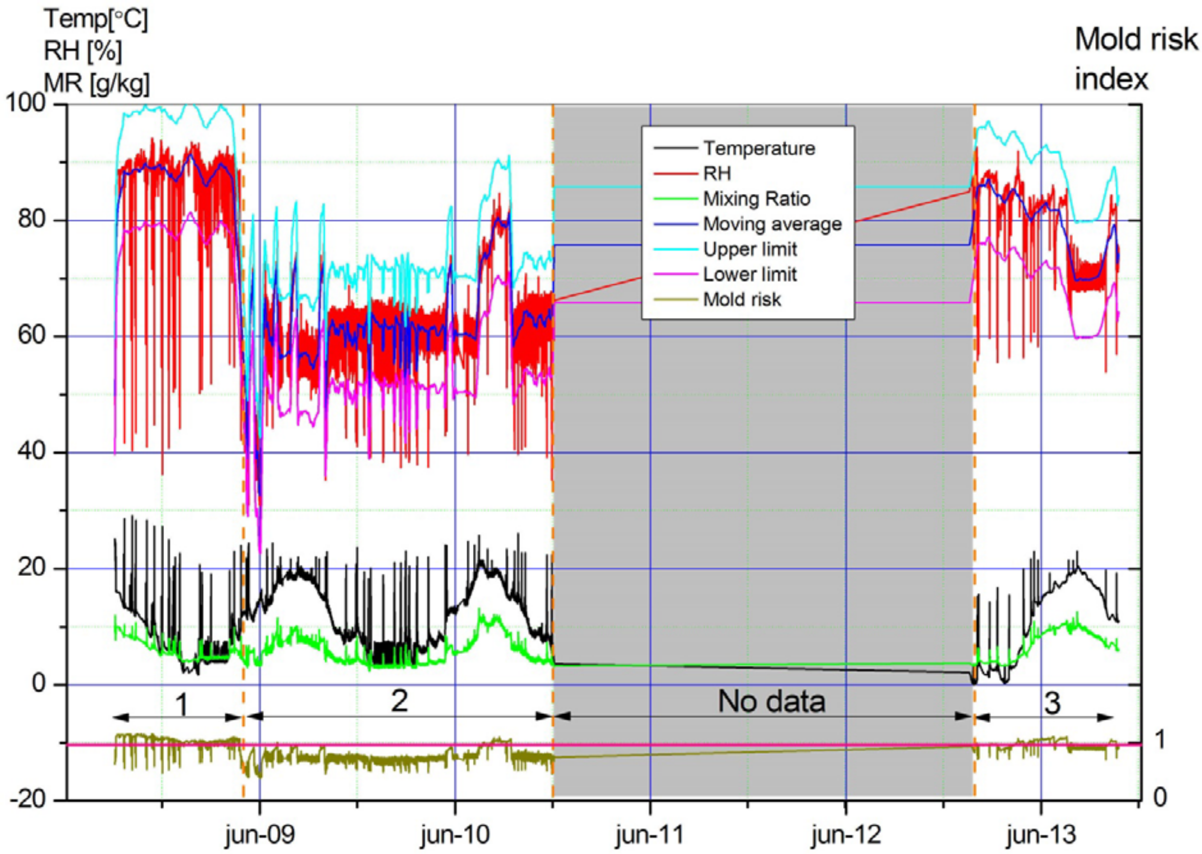


Figure 9.4 The indoor climate in Näs Church, Gotland, Sweden. 1: No climate control, 2: sorption dehumidifier, 3: Intermittent use of condensing dehumidifier.

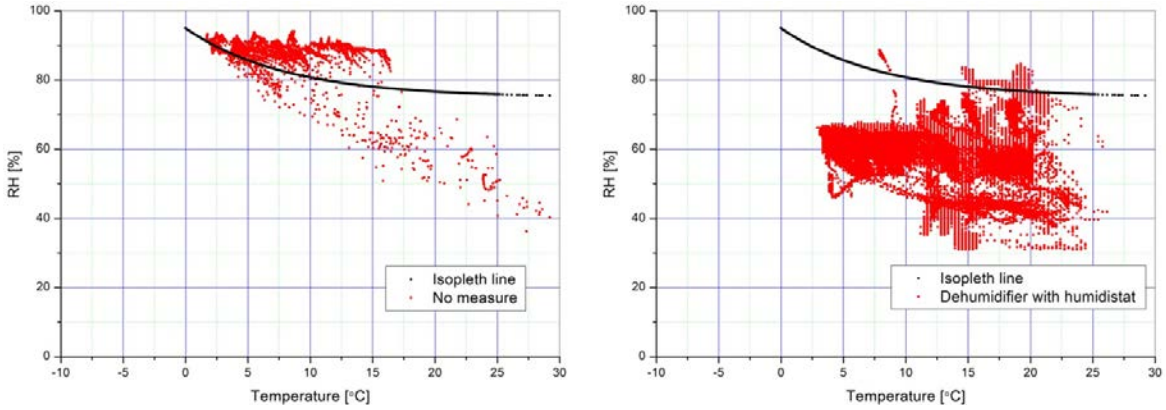


Figure 9.5 The indoor climate in Näs Church, Gotland, Sweden. Left: No climate control, Right: sorption dehumidifier.

The target range for the humidifier was initially 57 – 65%, later in the year it was adjusted to 60 – 70%. Figure 9.4 clearly shows the effectiveness of the dehumidifier. When the humidifier is in operation the RH level is kept within the target range. When the humidifier was incidentally turned off, the RH rapidly rises above 80%. For a brief period, the humidifier ran continuously, without control, and the RH decreased down to 35%. Figure 9.5 shows how the mould risk is eliminated by using the dehumidifier, the exception being periods when the dehumidifier was not in operation. In a short time period, RH levels were reduced and kept below risk levels. The annual energy consumption was 6.5 MWh, primarily due to a high humidity load in the summer.

After one year of operation the church had dried so much that a smaller dehumidifier was installed. When properly operated, this smaller dehumidifier was sufficient, however there was a long period when it was more or less turned off, which can be seen from Figure 9.4.

9.3.3 Case study – Fide Church

Fide church is a sandstone church located on the southern part of Gotland, Figure 9.6. In the winter, the church is used infrequently with no background heating. After reports of bad smell, especially in the summer time, it was decided to install a condensing dehumidifier. There were four different stages of operation which were monitored:

1. No climate control
2. Small condensing dehumidifier with humidistat control (set value of RH)
3. Small condensing dehumidifier controlled with respect to the mould risk curve, i.e. at lower temperatures, higher RH was allowed.
4. Big condensing dehumidifier controlled with respect to the mould risk curve

Figure 9.6 Condensing dehumidifier in Fide church.

Fig 7 and 8 show that both the RH and mould risk decreases by using dehumidification. Controlling RH with respect to mould risk curve, rather than a set value of RH gives lower energy consumption but the risk margin is smaller.

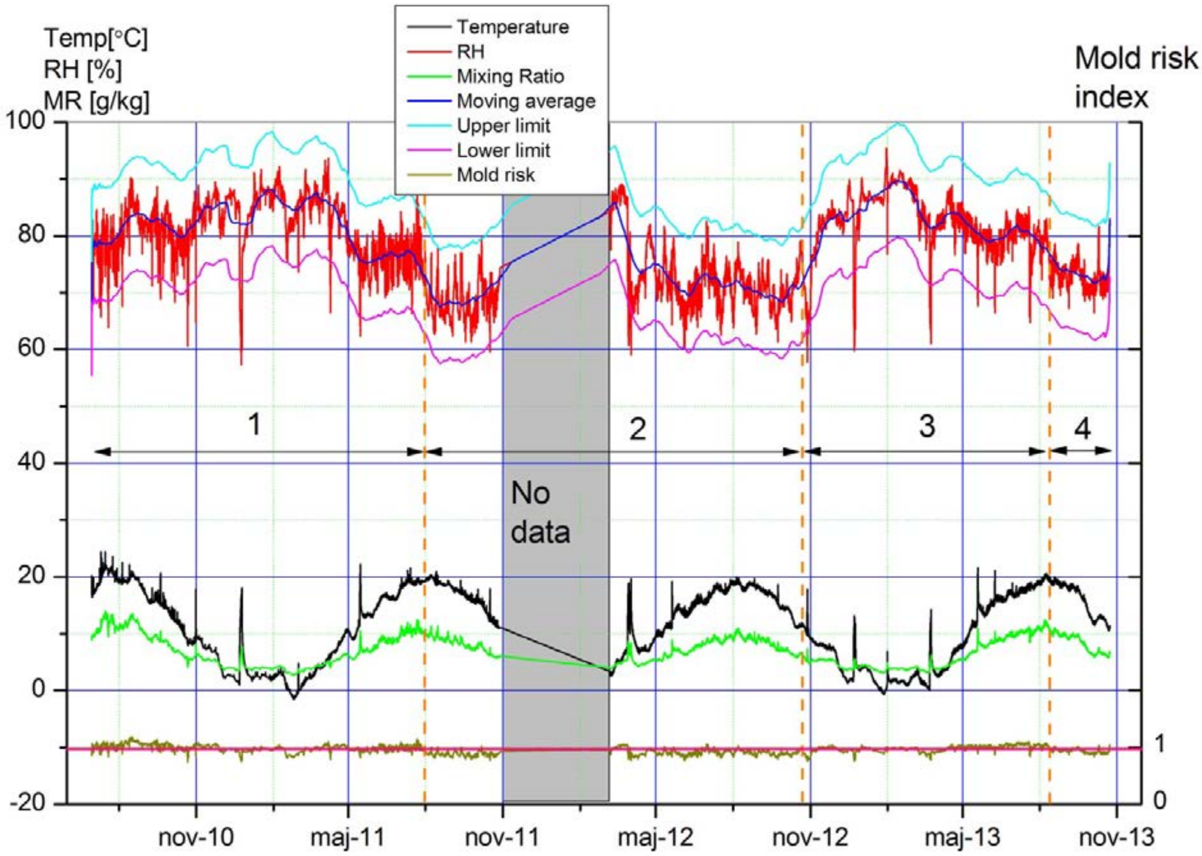


Figure 9.7 Indoor climate in Fide church. Four different stages of climate control see text above.

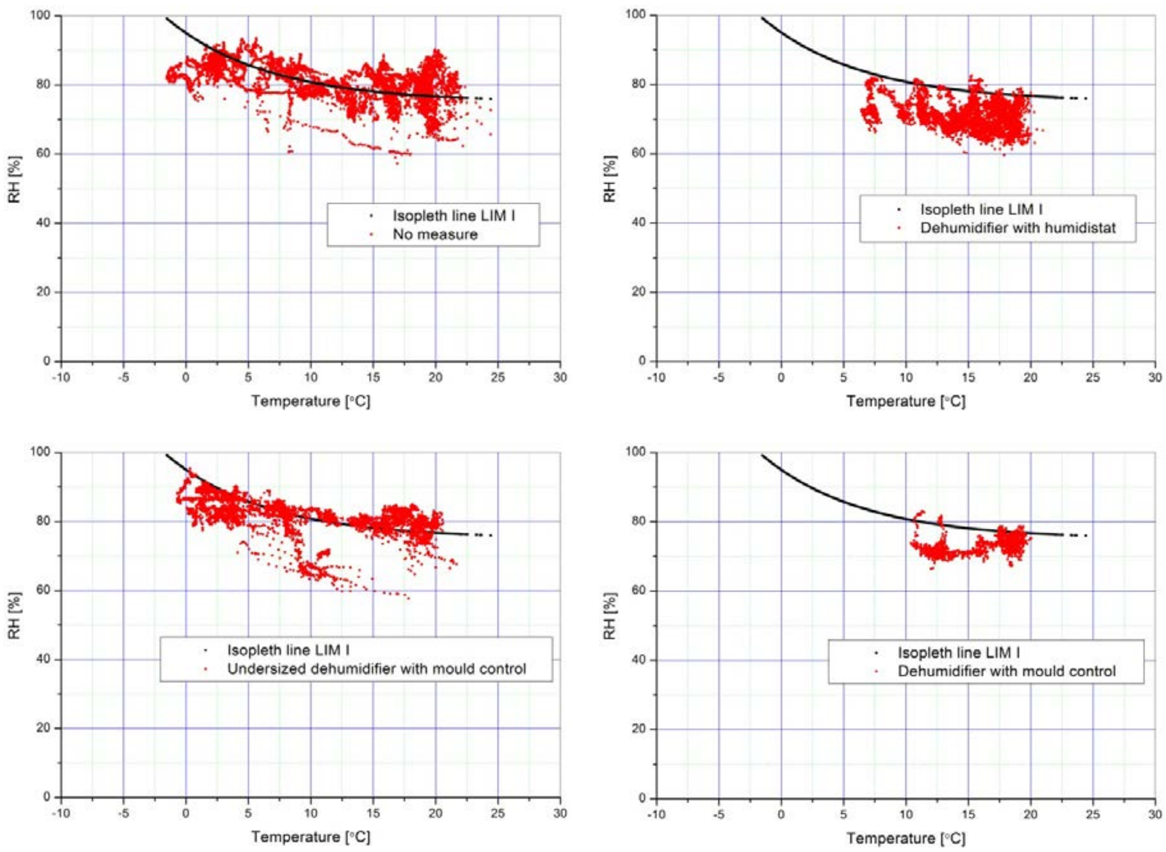


Figure 9.8 Indoor climate in Fide church. Four different stages of climate control, see text above.

9.3.4 Case study – Havdhem church

After reports of mould problems, a condensing dehumidifier was installed in Havdhem church. This is an 11th century church built in lime stone (Figure 9.9). When the humidifier was in operation, RH was kept at a target range of 70% fig 10. However irregular operation and/or malfunction impaired the performance of the humidifier during the second year of operation. Still mould risk was more or less eliminated, see fig 11, even though the risk margin was small.

Figure 9.9 Havdhem church.

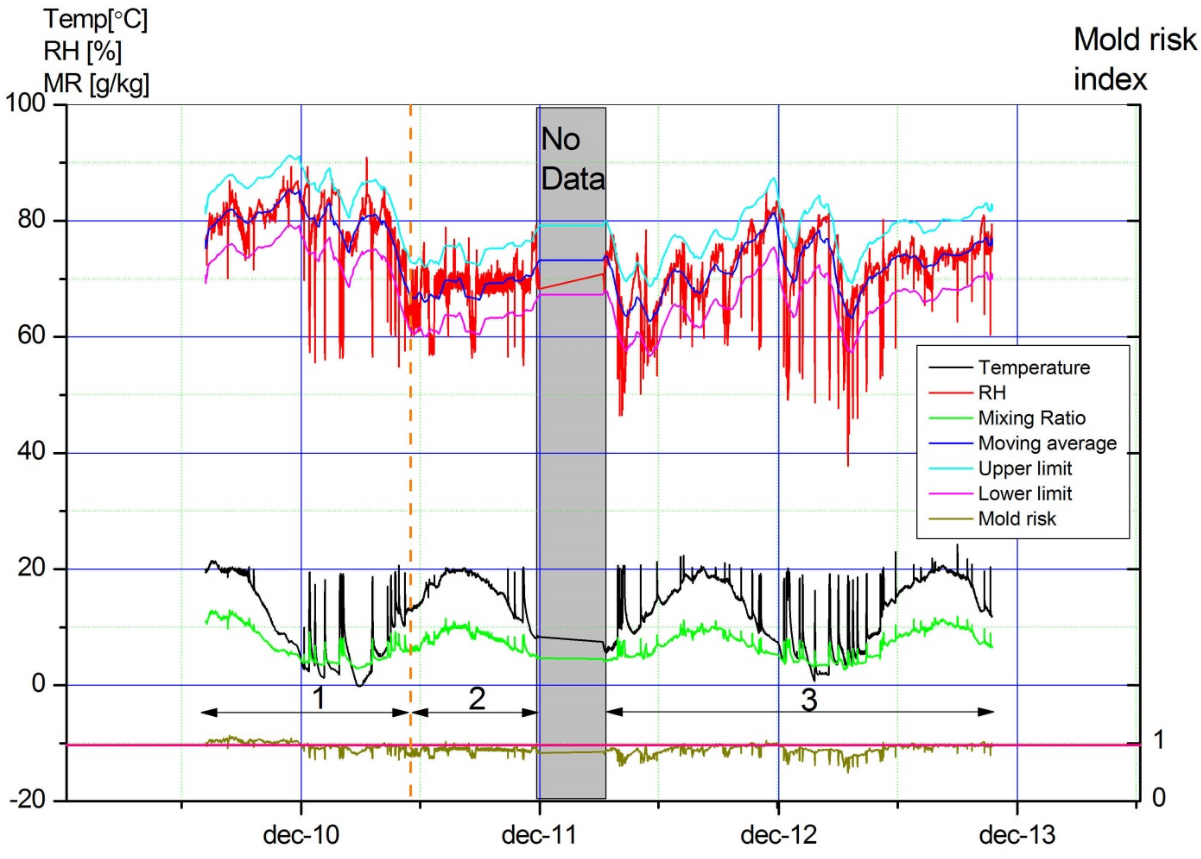


Figure 9.10 Indoor climate in Havdhem church

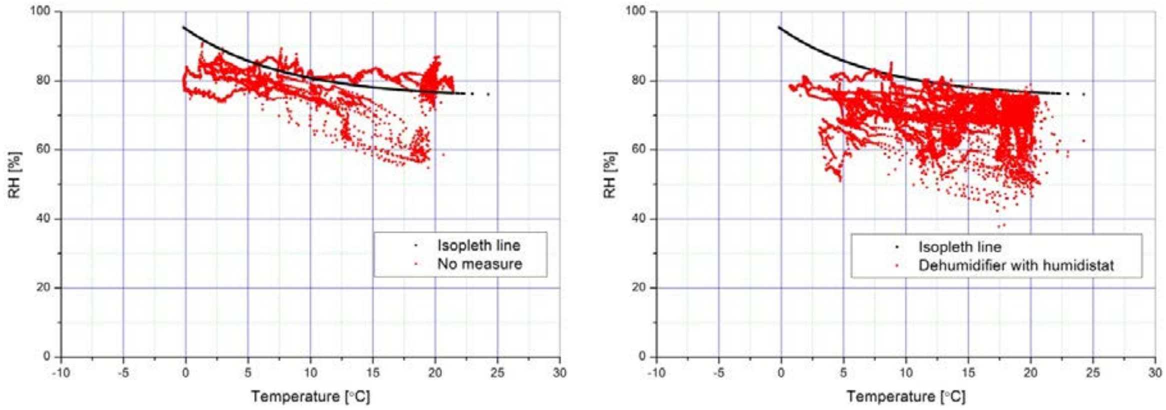


Figure 9.11 Indoor climate in Havdhem church. Left: no climate control. Right: Dehumidifier

9.3.5 Conclusions - dehumidifiers

During the last years, dehumidifiers have been installed in many Gotland churches. When the size is right and the equipment is used properly, they have been able to reduce and even eliminate mould risk.

The energy consumption of dehumidifiers is generally lower as compared to conservation heating. The only competitive heating option is to use heat pumps. The exact numbers depend on the construction and use of the building. In any case, the cost of dehumidification is marginal as compared to cost of dealing with mould problems that have occurred.

Finding the right capacity for the dehumidifier is critical. In some cases too small dehumidifiers have been selected. The operation and maintenance of the dehumidifiers is another critical factor. Too often the dehumidifiers have stopped due to technical problems or the simple fact that the condensation water container has been full. If possible one should select dehumidifiers that have the option to drain the condensate directly. In this case some kind of drainage is needed, either through a hole in the building or in existing drainage systems.

9.4 Adaptive ventilation

Air exchange through infiltration or ventilation has an important effect on the indoor climate in general and relative humidity in particular. Ventilation is the deliberate intake of ‘fresh’ outside air and simultaneous outlet of ‘used’ air from the interior. Infiltration is the random air leakage through cracks and openings in the building envelope. Opening windows and doors is a simple way of controlling the intake of outside air. But it is difficult for a person to decide when the climatic conditions are favorable for adjusting the indoor climate, and when it will have the opposite effect.

Adaptive ventilation is used to maintain a lower level of water vapor in the inside air than outside. Depending on outdoor and indoor climate conditions, air exchange can either increase or decrease the RH in a building. The controlling principle of adaptive ventilation is to ventilate only when the absolute humidity (AH) inside the building is higher than outside (Figure 9.12). This is done by taking advantage of the natural diurnal and seasonal variations in the outside absolute humidity. Equally important is not to ventilate when AH outside is higher. Thus, both air tightness and ventilation must be controlled and adapted through the use of mechanical fans and dampers controlled by indoor and outdoor climate sensors.

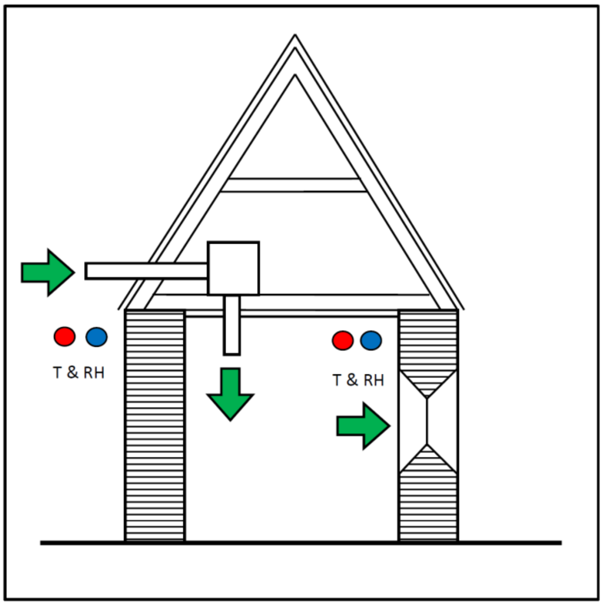


Figure 9.12 Principal diagram of a system for adaptive ventilation. The operation of the fan is controlled by a small computer connected to the inside and outside sensors for temperature and relative humidity.

Adaptive ventilation was implemented in the Torhalle in Lorsch, Germany, where condensation on the wall paintings was avoided by mechanical fans controlled by indoor and outdoor climate sensors (Reiss 1993). In the church in Zillis, Switzerland, controlled ventilation was used to stabilize RH in favor of the painted wooden ceiling. The effort was not very successful due to a large infiltration rate and the fact that ventilation was turned off in winter to reduce heat loss Bläuer-Böhm et al 2001). A seasonal use was tested in the Antikentempel in Potsdam-Sanssouci Park to prevent mould growth on the walls and ceiling. From May to September there was adaptive ventilation by a fan mounted in the skylight (Brockman 2010).

In the above mentioned cases the control system was custom designed for the individual purpose. But there are commercial solutions available which are intended for attics and crawl spaces under houses (Hagentoft 2008). Such equipment was used in a historic building on Gotland (Broström et al., 2011) and churches in Denmark and on Gotland (Larsen et al., 2013). The study on Gotland confirmed that adaptive ventilation is particularly useful when there are internal moisture sources in the building resulting in absolute humidity levels higher than outside. However due to the covariance of temperature and absolute humidity in the outside air, the effect on relative humidity inside a buildings is limited in the short term. In a typical diurnal cycle the temperature will be lower outside when the MR is higher inside and the fan is running. This means that the ventilation has a cooling effect that would tend to increase RH, even though moisture at the same time is removed from the building.

This chapter presents a summary of the results from a case study that was carried out within the SMC project. In addition to this, two Danish case studies are provided for reference.

9.4.1 Case study - Hangvar church

Background

The section presents results from a medieval stone church where a novel integration of solar heating and adaptive ventilation has been implemented. Solar energy is collected in the day and stored. In the night, when the outside air generally is drier (in absolute terms), outside air is preheated using the energy stored in the daytime and added to the building.

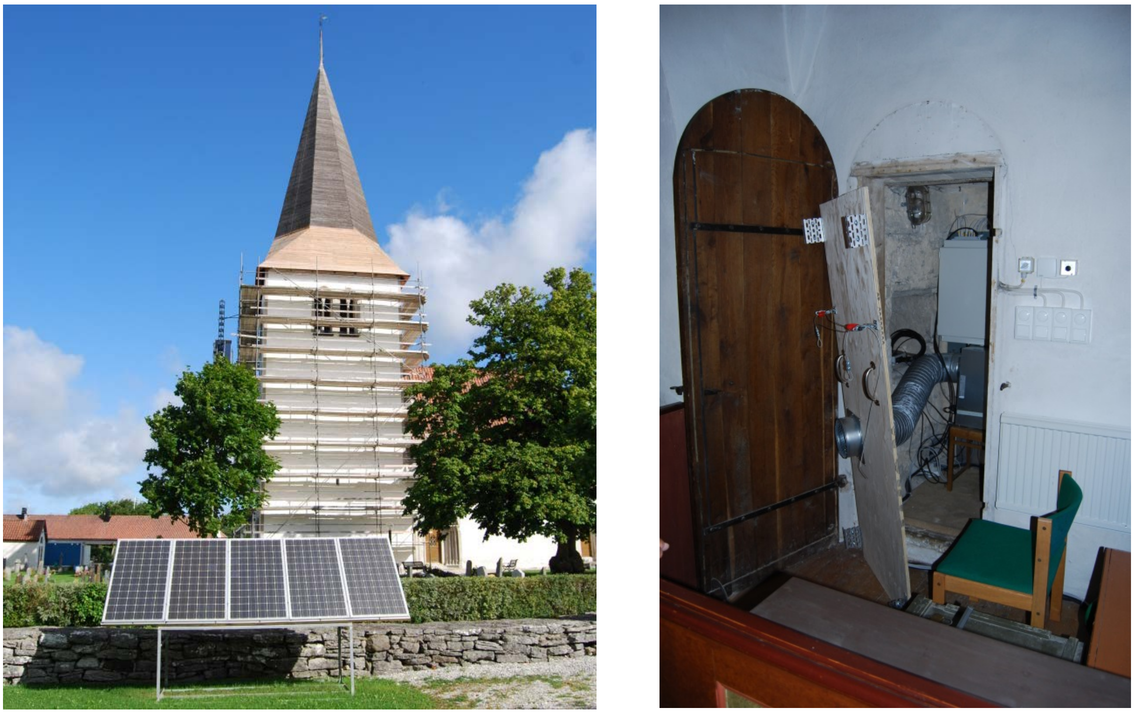


Figure 9.13 Hangvar church with the photo voltaic elements place outside the churchyard and the temporary installation of the fan on the tower staircase.

The previous studies have indicated that the cooling effect due to the covariance of temperature and AH is a limitation to the effectiveness of adaptive ventilation in historic buildings. The proposed solution is an integration of solar energy and adaptive ventilation. Solar energy was seen as a sustainable solution both in terms of resource use and economy. The concept operates as follows:

- In the day time, solar energy is collected and stored.
- At night, when the outside air generally is drier, the inlet air is preheated using the stored energy.

The system can either be electric (photovoltaic) or thermal (air based) depending on costs and practical aspects. In this study, an electric system was used (Figure 9.13).

The church building

Hangvar church is a 13th century stone church situated on the North West part on the island of Gotland, Sweden. The construction is typical for Gotland churches with outer walls and vaults made of lime stone in lime mortar and a roof construction of wood with tiles. The volume of the nave and chancel in total is 1000 m^3. The church is used only some 10 times per year, mostly for funerals and weddings. The church is intermittently heated for services and unheated in between. During winter the indoor temperature can go down below zero. The church has been very humid. During springtime there has been condensation on walls and floors. The members of the parish have complained about bad smell and there had been visual growth of algae and mould in corners and on the northern wall. Many tourists visit the church during summer and the church door has been left open in the day time.

Measurements of the church´s air tightness were carried out in August 2013. Two different methods were used (Figure 9.14). The blower door test (EN 13829, 2000) showed a result of Q_{50} = 0.89 l/s/m^2 and the pressure pulse method (Cooper Et Al., 2007) showed on a resulting equivalent leakage area at 4 Pa of 0.051 m^2. Both methods showed a result of Q_4 = 138 l/s which is in the same magnitude as the adaptive ventilator fan in full speed.

Figure 9.14 The air tightness of the church was measured using two different methods.

Technical solutions

The adaptive ventilation system was installed in July 2012. The system used is a commercial system (Hagentoft et al., 2008) mainly intended for attics. It consists of a control unit, an indoor sensor, an outdoor sensor and a fan. The fan runs if the outdoor partial pressure of water vapour is 10% lower than indoor value. The control unit has logging facilities for indoor and outdoor temperature and RH, fan speed and the relation between indoor and outdoor water vapour partial pressure.

The fan speed is adjustable and from July 2012 to December 2012 the ventilator speed was set to run proportional to the difference between indoor and outdoor water vapour pressure starting at 50% of max speed. From January 2013 the fan speed was set to run at 100% any time the water vapour pressure is 10% lower outdoors than indoors.

In the inlet air duct there are two electric heaters with a total power of 1800 W.

The case study was designed for 25 m^2 of photovoltaic elements. But due to costs and the fact that this set up is experimental and temporary, only 5 m^2 were installed. Therefore the amount of produced energy is multiplied by 5 in the control system. The photovoltaic elements where placed outside the church yard in order to avoid a discussion on the visual impact of roof placement. In this case the electric grid is used to store the energy, rather than a local storage. A DC to AC converter is connected between the photovoltaic panels and the grid via an energy meter which in turn is connected to the intake air heater control system.

The heaters are controlled by control system developed In LabView. The system compares the amount of produced energy from the photovoltaic elements energy meter and the consumed energy by the heaters energy meter. The heater is only set to run when there is a surplus of solar produced energy at the same time as the ventilator is running.

Results

Indoor climate

From July 2010 to June 2012 there was no climate control in the church except for the heating periods for services. There was no climate monitoring between December 2011 and March 2012.

Figure 15 shows the indoor climate over three years. It can be seen that the average relative humidity has decreased but the variations; both short term and long term have increased. To better compare the measures two one-year periods are chosen and table 1 shows a statistical summary from the time period without any climate control, September 2010 to August 2011 and the time period with adaptive ventilation September 2012 to August 2013.

The statistical summary shows that average relative humidity has decreased from 81 to 76%. The average temperature is approximately the same for the two periods, just 0.2 degrees of difference.

The short term variations in RH are important from a conservation point of view. A European standard, (EN15757) provides a method to determine a target range for short term variations in RH in relation to a moving seasonal average. Deviations of less than ±10% RH are considered safe. Figure 9.15 shows that when using adaptive ventilation there are more short term excursions outside the target range. The standard deviation, in relation to the moving average increase from 3.5 percentage points to 5.2.

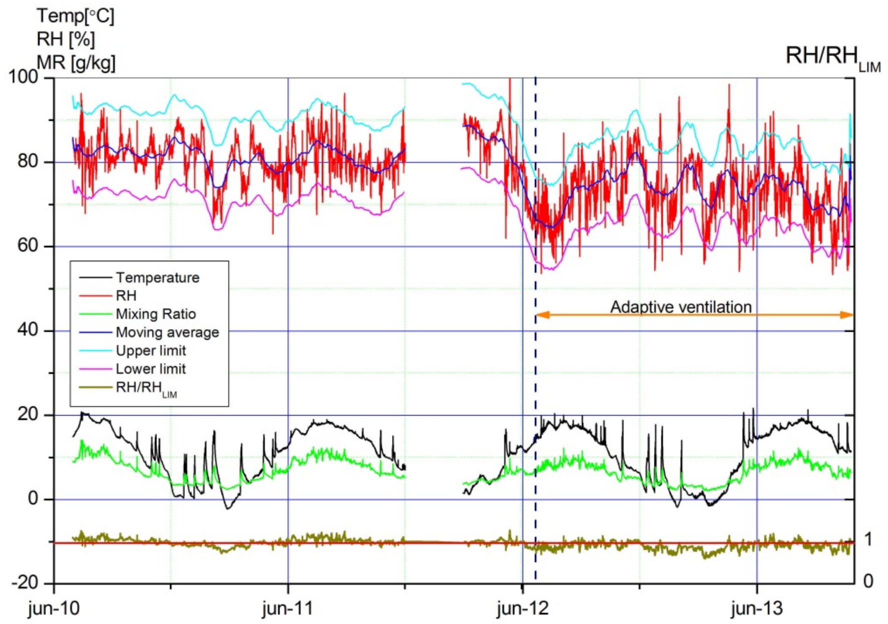


Figure 9.15 Indoor climate in Hangvar church. The graph shows that during the period with adaptive ventilation the relative humidity in average has decreased but the variations have increased.

Table 9.1 Statistics for the two periods

Period	Average Temperature	Average RH	Average MR	Standard deviation of short term fluctuations
Without climate control	9.6	81	6.5	3.5
Adaptive ventilation	9.3	75	5.9	5.2

Mould prevention

Mould risk is assessed in relation to the isopleth curve LIM I, biologically recyclable building materials (Sedlebauer 2001). Figure 9.16 shows the period without climate control and the period with adaptive ventilation. It is clear that the risk for mould has decreased the year with adaptive ventilation (Sedlebauer 2001). The year without climate control, 44% of the time the indoor climate was above the LIM. When the adaptive ventilation system was running only 16.7% of the time the indoor climate was above the LIM.

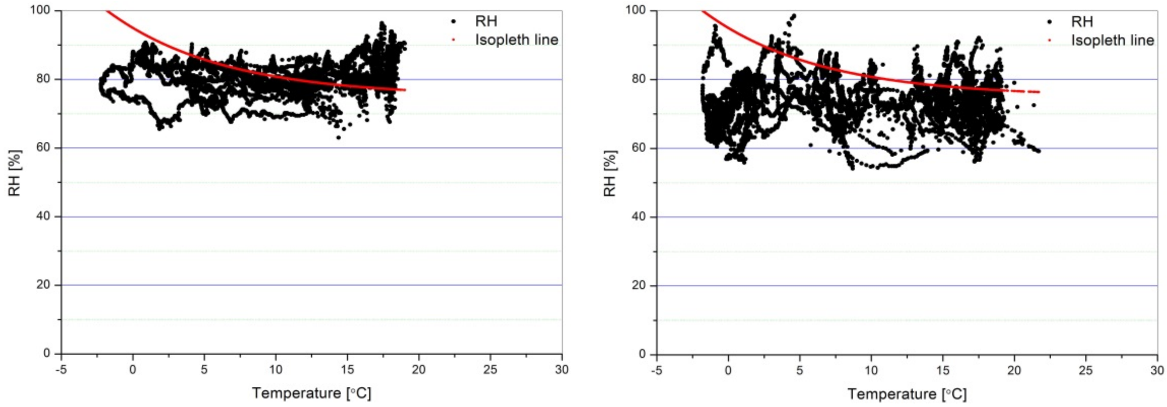
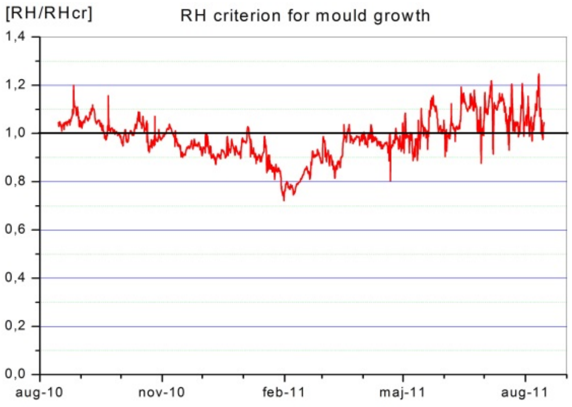


Figure 9.16 Damage functions for mould. Left: time period without climate control. Right: time period with adaptive ventilation.

The duration in the area above LIM is critical for mould growth. In the year without climate control the average duration length above LIM was 72 hours and the longest period was 826 hours. In the year with adaptive ventilation, average was 32 hours and longest period 134 hours.

Figure 9.17 shows RH/RH_{LIM} where RH_{LIM} is the lowest isopleth for mould. If the value is above 1, the climate is beneficial for mould growth. According to (Sedlebauer 2001) the climate has to be above 1 for longer periods (days) to make it possible for mould to grow. It is clear that the time periods with favourable condition for mould growth are fewer have shortened with adaptive ventilation.



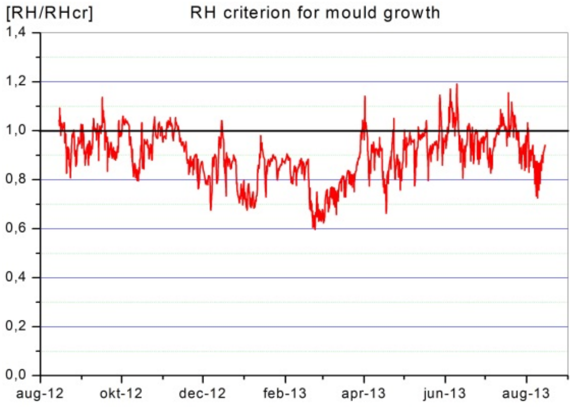


Figure 9.17 RH/RH_{LIM}. Left: without climate control. Right: with adaptive ventilation

The duration graph (Figure 9.18), show that even small changes in the RH levels have a significant impact on climate control requirements. Figure 9.18 shows the duration graph for RH/RH_{LIM} where RH_{LIM} is the lowest isopleth for mould. If the ratio RH/RH_{LIM} is 1 or above, the climate is beneficial for mould growth.

If the requirement is to have $RH/RH_{LIM} < 1$ the demanded time for use of dehumidifier was 1450 hours in combination with adaptive ventilation while it was 3750 hours without climate control?

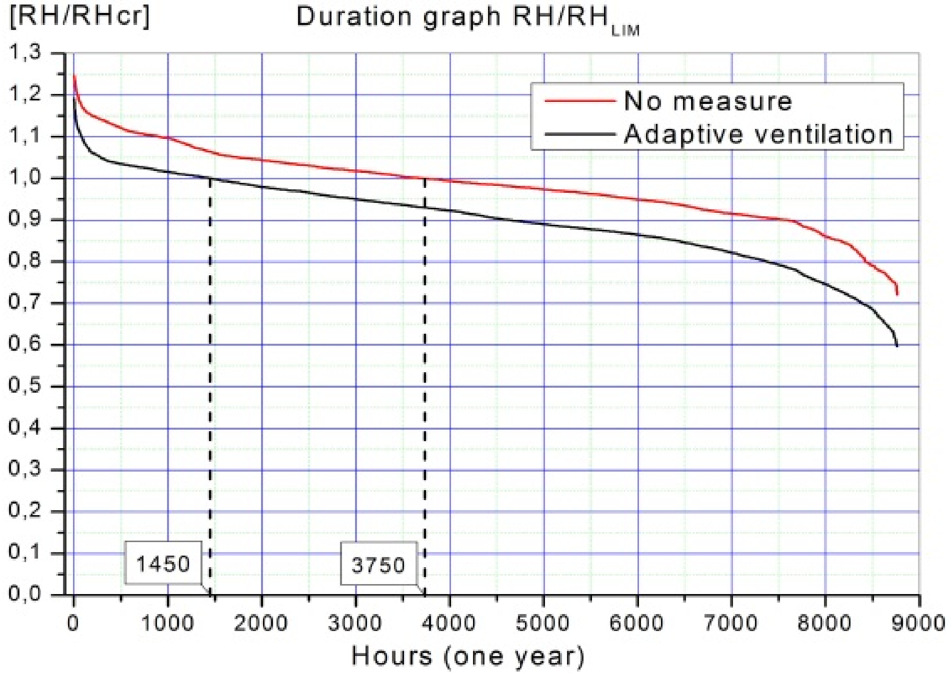


Figure 9.18 *Duration graph of RH/RH_{LIM}.*

Based on the difference between mixing ratio indoors and outdoors every hour and the air flow, the total moisture transport during the test period is calculated. From September 2012 to August 2013, 1100 kg of water was transported out of the church. The ventilator has consumed 250 kWh of electrical energy during the same period. This gives a drying efficiency of 4.4 kg water per kWh.

Energy from photo voltaic panels

The inlet air heaters are used only when there is stored solar energy available and the ventilator is running. In October, November, December and half of January the solar panels did not produce enough energy for preheating the whole time when the ventilation was in operation (Figure 9.19). In the rest of the year the produced energy was larger than the amount of consumed energy.

From September 2012 to August 2013 the 5m² photo voltaic panels have produced 645 kWh, thus the imaginary panels of 25m² produced 5 · 645kWh = 3 225 kWh. The amount of energy used for the inlet air heaters was 2 066 kWh.

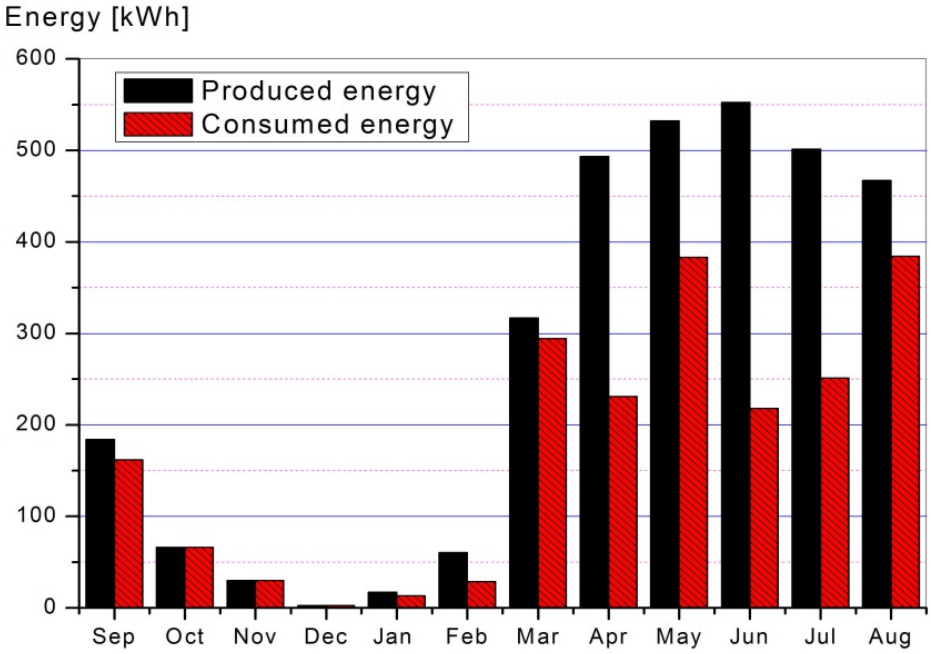


Figure 9.19 Monthly produced and consumed solar energy.

When the fan is running at full speed the heaters gave a temperature difference of 11 °C. When solar energy has been available, this has generally been sufficient to counteract or mitigate the cooling effect without causing any harmful temperature variations.

In January 2013 there was no solar energy available. During one week, the adaptive ventilation ran without preheating and the indoor temperature decreased by 6 °C. At the same time the MR decreased and RH still was around 65%.

Conclusion from the Hangvar case study

This case study shows that adaptive ventilation has improved the indoor climate in the church. During one year, some 1100 kg of water has been removed from the building resulting in significantly lower RH level and reduced mould risk. The members of the parish have felt that the indoor air quality has improved, mainly in the elimination of bad smell. Short term variations have increased slightly, but they are still mainly within acceptable limits.

Adaptive ventilation is a low-cost and low-energy option as compared to conventional humidity control. The annual energy consumption for the operation of the fan was 250 kWh. Overall this gives an efficiency of 0,22 kWh/kg which is an order of magnitude smaller than for conventional dehumidifiers.

The preheating of the inlet air has counteracted the cooling effect that was reported in previous studies. During one year, the contribution from the solar panels was 2000 kWh. This is economically viable only if the solar panels are subsidised.

In this case adaptive ventilation is not sufficient to eliminate mould risk throughout the year, however it does significantly reduce the operational time and energy demand for auxiliary measures such as dehumidification. The results are from the first year of operation, over a longer time period the massive structure are expected to slowly become dryer thus reducing indoor RH levels.

A general problem with adaptive ventilation in historic buildings is achieving sufficient air tightness. The air tightness measurements indicate that the air leakage maybe of the same order of magnitude as the ventilator air flow.

In future investigations different strategies for the control of ventilation and preheating will be investigated through building simulations and further field trials, both over longer time periods. This would include an assessment of thermal solar air systems with local heat storage.

9.4.2 Case study - Nødebo Church

Nødebo Church is situated in a forest area on Zeeland, Denmark (Figure 9.20). It has a medieval nave and chancel with outer walls made of boulders laid in lime mortar, and vaults of fired bricks. The total volume of the space is 400 m^3 . Nødebo church has intermittent heating for services in winter with basic heating to a constant temperature of 8 ˚C in between. The climate record for three years is shown in Figure 9.21. The relative humidity inside the church is down to 60%RH in winter due to the basic heating. In summer the RH gets above 90%RH if nothing is done to avoid it. This happened in the summer of 2011, where the data logger failed for some time due to condensation on the sensor. The main problem in summer is that the temperature is too low. It is a common problem for many churches that the solar gain is little, because there are only few and small south facing windows. Summer heating was implemented the year before in 2010 to overcome this problem. By heating the church a few degrees above the outside average to a maximum of 23 ˚C, it was possible to keep the RH below 80% most of the summer. Still the RH was above 80% for a few weeks during September and October. Summer heating is a possible, but not very energy efficient solution to the problem of high relative humidity in the summer.

Figure 9.20 Exterior view of Nødebo Church from the south east. Solar heating of the interior through the small windows is too little to heat up the interior in summer.

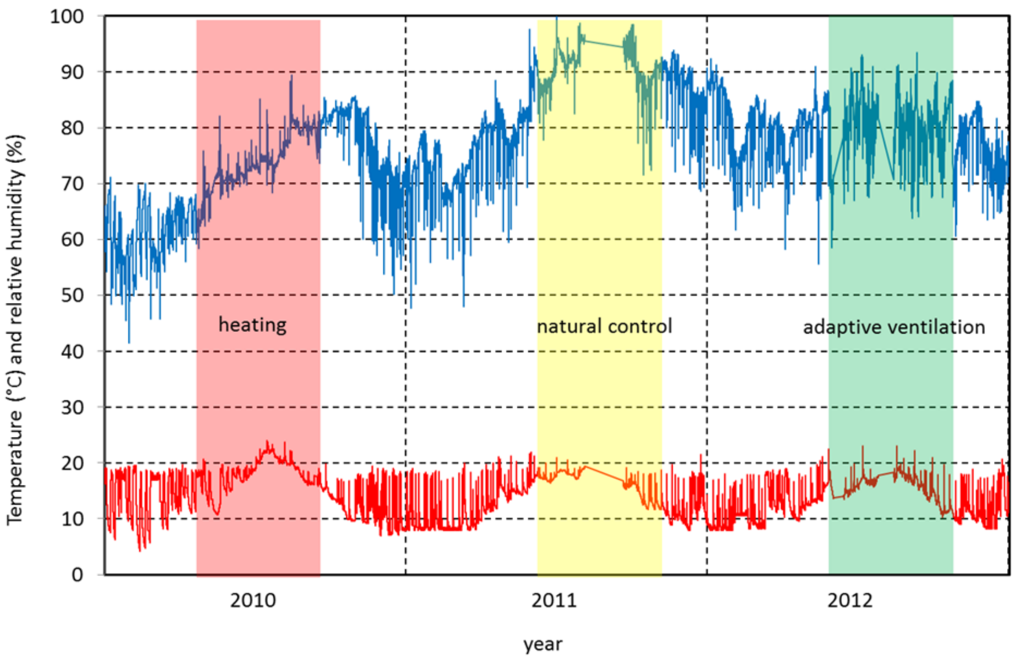


Figure 9.21 Climate record from Nødebo Church over three years. The first summer had heating to keep the RH below 80%. The next summer had no control and the last summer had adaptive ventilation

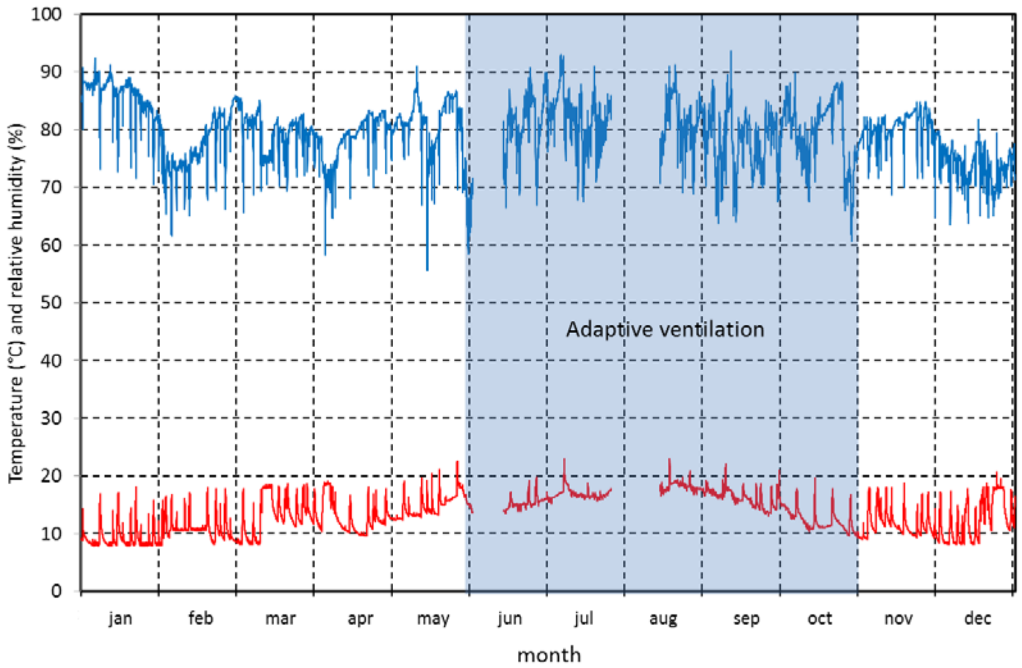


Figure 9.22 Climate record from Nødebo Church in 2012. Adaptive ventilation was operated from the beginning of June until the end of October, when background heating was started.

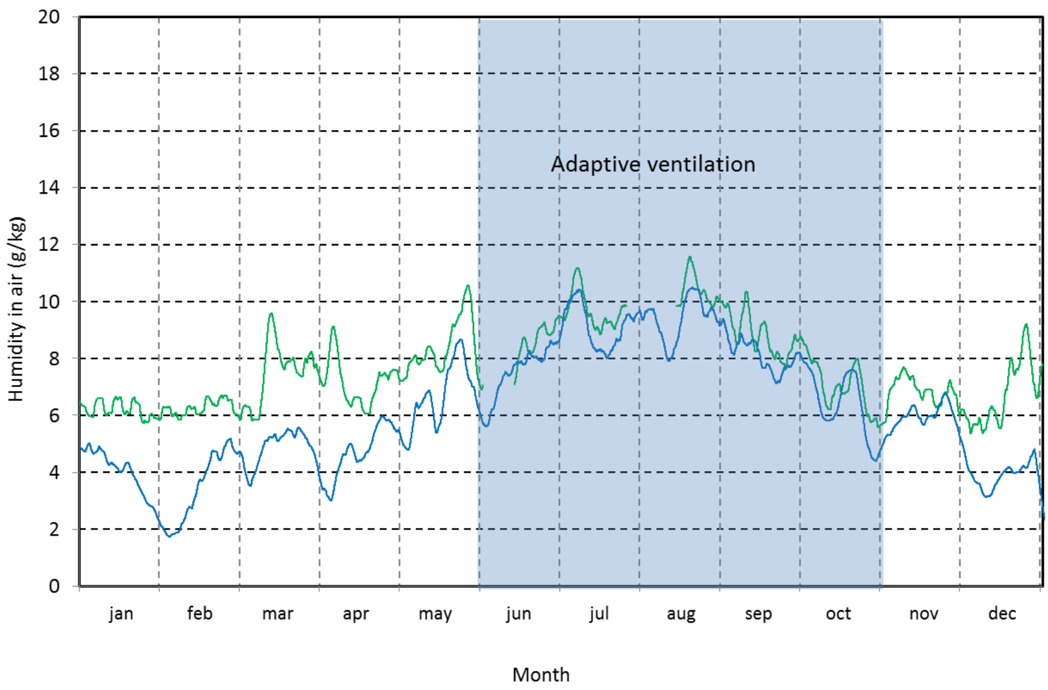


Figure 9.23 The mixing ratio of the inside and outside air in Nødebo Church shown as a moving average over 7 days. The inside MR is higher than outside in winter, but in summer they are equal due to the ventilation.

Adaptive ventilation was applied in the summer 2012 by the reuse of an old exhaust ventilation system. The fan was located in the attic of the entrance porch and the air was drawn through a grate in the wall on the organ pulpit. The fan had been controlled manually to operate after the Sunday ceremony. A control unit for adaptive ventilation was installed, which would start the fan at any time, if the outside air was drier than inside. The air intake was though leaks in the windows. The ventilation was on from the end of May until the end of October. The climate record for 2012 is shown in Figure 9.23, and the period with adaptive ventilation is the blue shaded area. In this period the inside RH was 65 – 90% and the temperature up to 19 ˚C in August, apart from a few occasions with comfort heating to 22 ˚C.

It seems that the short term fluctuations in RH were larger with adaptive ventilation than before. This is a known problem associated with ventilation in general, that the RH gets more unstable. The RH over the summer was clearly lower than the year before, but still too high to prevent biological activity. However the bad smell of fungi was entirely gone. A further benefit of the ventilation was a significant improvement of the air quality. The effect of ventilation on an annual range was evident when comparing the mixing ratio of the inside and outside air. Over the summer the water vapour content inside was almost equal to that outside. During the winter the inside was always more humid than outside (Figure 9.23). This is because the winter heating promotes the evaporation of moisture from the floor or walls to the interior. This is an argument against heating for controlling the RH, and to use adaptive ventilation all year.

9.4.3 Case study Tyvelse church

Tyvelse Church is situated in the countryside on Zeeland, Denmark (Figure 9.24). It has a medieval nave and chancel with outer walls made of boulders laid in lime mortar, and vaults of fired bricks. The interior volume is app. 400 m3. The wall paintings in the chancel vault have a severe infestation of mold growth. The climate record from 2007 showed that the temperature ranged between 5 °C in winter and 22 °C in summer. Despite of the basic heating in winter, the interior RH was between 80 and 90% most of the year. The church was rarely used, so the high RH was not due to human activity. The absolute humidity inside was above that outside for most of the time. The data for temperature and relative humidity is plotted in the diagram in Figure 9.25. The red line indicates the limit for mold growth, whereas the green line is an approximation of the conditions needed for wood worms to develop. It is evident that the climate was almost ideal for biological degradation.

An old ventilation system installed some year ago was reused for adaptive ventilation. An exhaust fan in a window had been controlled by a timer to operate at the same time each day. This was replaced by the control unit for adaptive ventilation, which would start the fan at any time, if the outside air was drier than inside. The fan had a damper which would be closed when the fan was not running. The air intake was though 12 small ducts in the lower part of the vaults. These openings remained open at all times. The advantage of taking the air from the attic was that there would be some preheating in the summer. On sunny days the temperature in the attic was higher than in the nave below due to the solar gain. It was assumed that warm air from the attic would raise the interior temperature in the nave slightly, and thereby lower the RH.

Figure 9.24 Exterior view of Tyvelse Church from the northeast. The air supply to the nave and chancel was drawn from the attic to gain heat from the solar radiation to the tiled roof.

The basic heating in winter was abandoned, so the winter temperature was lower than before, below 0 ˚C. The summer temperature was no different than before, up to 22 ˚C. This indicates that the attempt to preheat the intake air through the attic was not very successful. The relative humidity was 10-15%RH lower than before, but there were still episodes where it exceeded 90% RH. The annual climatic variation was larger than before, but the short time fluctuations did not increase. Apparently the attic served the purpose of ameliorating the outside air before it was drawn into the nave and chancel. It is difficult to determine if the reduction in RH had an effect on the risk of mold and wood worms in general. But it is evident that the lower temperature in winter is a good measure against biological activity. Perhaps the main benefit of adaptive ventilation is that it excludes basic heating in winter.

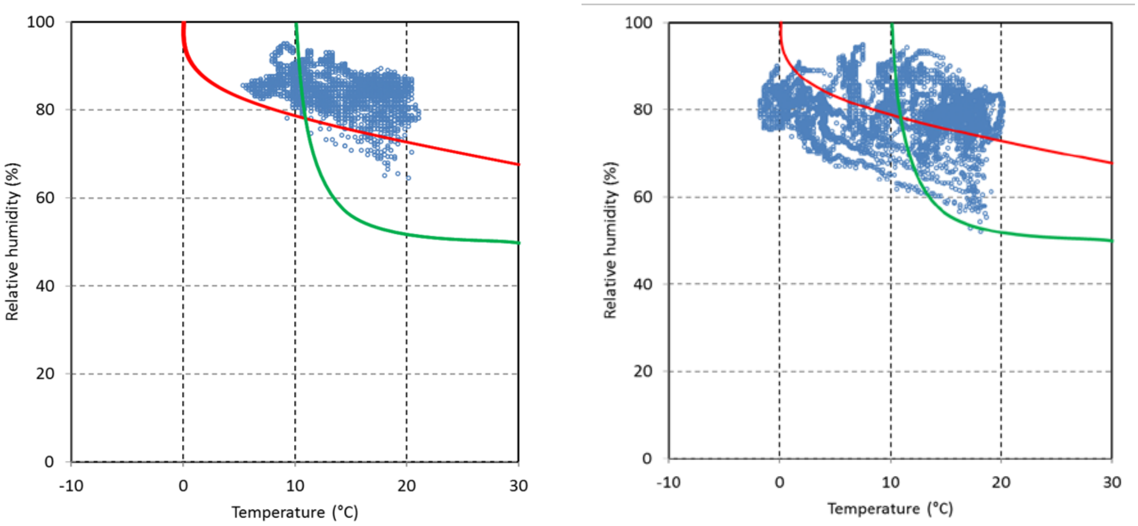


Figure 9.25 Climate record in Tyvelse Church with background heating in winter (left) adaptive ventilation (right). Limits for mold growth (red line) and wood worm (green line).

9.4.4 Conclusions on adaptive ventilation

There is a need for a low energy climate control strategy for churches, which are used occasionally. Adaptive ventilation is an efficient method for churches with an internal source of humidity. It will reduce the inside mixing ratio towards the same level as outside. This is sufficient to prevent mold growth when the temperature is low enough. But in summer additional climate regulation may be required in buildings with little solar gain. This is a very common situation for medieval churches, because the windows are few and small. Preheating of the intake air with an electric element will possibly raise the temperature slightly and thereby lower the RH. This solution is almost energy neutral if a solar panel is installed to supply the heating power. Adaptive ventilation is a robust and reliable climate control solution, which is important for rural churches where resources for maintenance are limited. The challenge remains that the installations must not interfere with the use of the churches, and the visual and physical impact should be minimized.

9.5 Conclusion

There are different climate control strategies for churches, which are used occasionally. The aim is to avoid biological degradation, so the set point and the allowable variation for RH is the important parameter. The energy consumption should be minimized to ensure a sustainable solution. Passive climate control is in general not sufficient to prevent biological degradation. Never the less, in some unheated churches the interiors have survived for centuries in a humid environment without any climate control. This is possibly due to the low temperature in winter. Conservation heating should only be implemented if at the same time there is a need for human comfort. This is relevant for churches, which are used once in the week or more, and therefore needs intermittent heating. A heat pump is particularly efficient for conservation heating, because it performs well with a small temperature difference. Dehumidification is generally more energy efficient than conservation heating. A condensation dehumidifier is useful in summer, when the temperature is above 10 °C, or in combination with moderate heating in winter. A sorption dehumidifier is to prefer if the church is not heated, because it works at low temperatures. Adaptive ventilation can possibly be used to keep the RH below the limit for mould growth or avoid condensation on cold walls or floor. It is particularly efficient for buildings with an internal source of humidity. In combination with a low infiltration rate, this method is the most energy efficient strategy. In addition to the technical requirements, the climate control solutions for churches need to be robust and reliable as resources for maintenance are limited. Also the installations must not interfere with the use of the churches and the visual and physical impact should be minimized.

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- Climate monitoring: Testo AG, Testo-Straße 1, 79853 Lenzkirch, Deutschland, Tel: 07653/681-0, Fax: 07653/681-1559, E-Mail: info@testo.de

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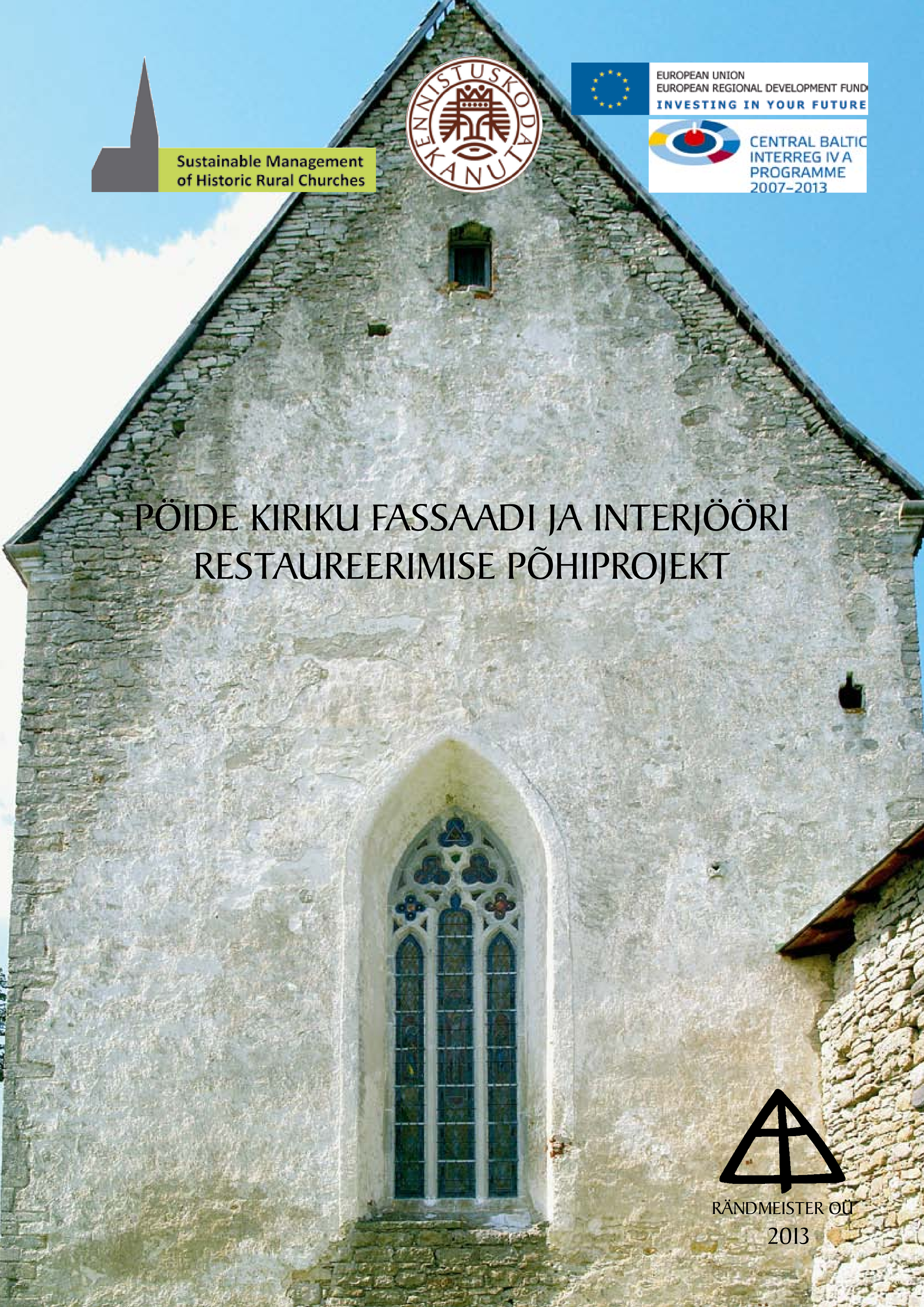
APPENDIX 1: CONSERVATION DOCUMENTATION OF FACADES AND INTERIOR OF PÖIDE CHURCH



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A Seletuskiri

1 Üldosa

1.1.1 Üldandmed

Käesolev restaureerimisprojekt on koostatud Ennistuskoda "Kanut" tellimusel Saare maakonnas, Pöide vallas asuva Pöide Maarja kiriku sise- ja välisviimistluse restaureerimiseks. Restaureerimisprojektiga lõpevad pikema-ajalised uurimistööd Pöide kirikus, mis viidi läbi programmi *Sustainable Management of Historic Rural Churches in the Baltic Sea Region (SMC)* raames 2012. a. Projektil on mitmeid koostööpartnereid ning see on osaliselt finantseeritud rahvusvahelise programmiga *Central Baltic INTERREG IVA programme 2007-2013.*

Kiriku omanik ja kasutaja on EELK Pöide Maarja kogudus. Kiriku säilimise ja taastamise eesmärgiga loodi 2012. a. Pöide Maarja Kiriku Sihtasutus.

Hoone ei ole arvel ehitusregistris.

1.1.2 Kinnistu andmed:

asustusüksus	Saare maakond, Pöide vald, Pöide küla
lähiaadress	Maarja
katastritunnus	63401:001:0430
kinnistu suurus	40,61 ha
ehitiste alune maa	1669 m^2
sihtotstarve	maatulundusmaa 100%

1.1.3 Projekteerija andmed

Rändmeister OÜ
reg. nr. EEP000399
Mõõna tee 15, 12112 Tallinn
juhataja Juhan Kilumets
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tel 51 57 157
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tegevusluba: E 113/2004-P

1.2 Projekteerimise alused

1.2.1 Kasutatud normdokumendid

Ehitusprojekti koostamisel on aluseks võetud Eesti Vabariigis kehtivad seadused, normid ja standardid:

- Eesti Vabariigi ehitusseadus
- Eesti Vabariigi muinsuskaitseseadus
- Kultuuriministri 04.07.2011 määrus nr. 15 "Kinnismälestiste ja muinsuskaitsealal paiknevate ehitiste konserveerimise, restaureerimise ja ehitamise projektide koostamise ning neis eelnevate uuringute tegemise tingimused ja kord";
- Majandus-ja kommunikatsiooniministri 17.09.2010 määrus nr 67 ''Nõuded ehitusprojektile'';
- EVS 811:2012 ''Hoone ehitusprojekt'';
- EVS 865:2-2006 Hoone ehitusprojekti kirjeldus. Osa 2: Põhiprojekti ehituskirjeldus;
- Vabariigi valitsuse 27.10.2004 määrus nr 315 ''Ehitisele ja selle osale esitatavad tuleohutusnõuded'';
- EVS 812:2008 "Ehitiste tuleohutus: osa 7. Ehitistele esitatava põhinõude, tuleohutusnõude tagamine projekteerimise ja ehitamise käigus";

1.2.2 Kasutatud uuringud ja projektid

- Pöide kiriku fassaadi ja interjööri seisukorra uuringud. Uuringute aruanne I. Välis- ja siseviimistlus. Koostaja: E. Mölder. Rändmeister OÜ, 2013.
- Pöide kiriku fassaadi ja interjööri seisukorra uuringud. Uuringute aruanne II. Maalingute leiud. Koostajad: A. Randla, H. Hiiop. Rändmeister OÜ, 2013.
- Pöide kiriku fassaadi ja interjööri seisukorra uuringud. Uuringute aruanne III. Raidkivid. Koostajad: M. Klammer, T. Sakermaa. Rändmeister OÜ, 2013.
- Pöide kirik. Muinsuskaitse eritingimused. Koostaja: J. Kilumets. Rändmeister OÜ, 2007 (ERA.5025.2.10051)
- Pöide kirik. Raidkiviakende restaureerimise ja avatäidete põhiprojekt. Koostaja: I. Kannelmäe. Rändmeister OÜ, 2008 (ERA.5025.2.4851)
- Saare maakond, Pöide vald, Pöide küla. Pöide kirik. Arheoloogilised uuringud Pöide kiriku põhjaküljel (Pöide ordulinnuse lõunatiib). Koostaja: J. Mäll. OÜ Agu EMS, 2000 (ERA.5025.2.8162)
- Pöide kirik. Välisviimistluse eskiisprojekt. Koostaja: T. Parmakson. R. Projekt, 1990 (ERA.T-76.1.9831)
- Pöide kirik. Välisviimistluse ja käärkambri tööjoonised. Köide "A". Koostaja: T. Parmakson. R. Projekt, 1990 (ERA.T-76.1.9832)
- Saare maakond, Pöide vald, Pöide küla. Pöide kirik. Restaureerimistööde aruanne 1995-1998. Koostaja. T. Sepp. OÜ Frantsiskus, 1998 (ERA. 5025.2.5417)
- Pöide vald. Pöide kirik. Arhitektuursed ülesmõõtmisjoonised. Kd. I. koostaja:

V. Malmre. TRT, 1958 (ERA.T-76.1.13455)
- Eesti keskaegsete raiportaalide inventariseerimine. Kingissepa rajoon. Koostaja: T. Parmakson. KRPI, 1985 (ERA.T-76.1.11237)
- Pöide kiriku väljakaevatud varemete ümbruse vertikaalplaneerimine. OÜ H. Uuetalu, 2001
- Pöide vald, Pöide linnus ja kirik. Asendiplaan. Koostaja: U Hermann. VRV, 1975 (ERA.T-76.1.2222)

1.2.3 Lähteülesanne

Kuna peale katusetööde lõppemist k.a. sügisel saab võimalikuks seni väga niiskete välisseinte ja võlvide kuivamisprotsess, on hädavajalik edaspidine sisekliima stabiliseerimine ja kontrollimine. Käesoleva projektiga lahendatakse kiriku paremaks ventileerimiseks portaalide tuulutusvõred ja puuduv põhjaportaali uks; antakse lõunaukse restaureerimise töökirjeldus. Pikihoone pööning eraldatakse teistest hooneosadest tuleohutuse eesmärgil tuletõkkeustega.

Pikihoone ja torni esimese korruse raid- ja tellispiitadega gooti kiriku aknaavadesse on 2008. a. valminud projekt vitraažakende paigaldamiseks. Projekt on väga hea ja võiks säärasena realiseeruda. Seega ei ole käesolevas projektis gooti kiriku aknaid käsitletud. Torni avad remonditakse ning neisse nähakse ette luugid ja linnukaitsevõrgud. Tornikiivri taastamist ei ole selle projektiga ette nähtud.

1.3 Üldülevaade

1.3.1 Senised uurimis- ja ehitustööd

Pöide Maarja kirikut on uuritud, projekteeritud ja ehitatud mitmel ajajärgul etappide kaupa. Ulatuslikumad uurimise-, fikseerimise-, projekteerimise- ja ehitustööd pärinevad 1957.–1960. aastast, mil kirik mõõdistati, uuriti selle tehnilist seisukorda, koostati katuse ja torni konstruktiivsed projektid. Pikihoonele valmis uus katus, kuid tornile jäi kiiver tegemata, selle asemel kaeti torni kiviosa madala konserveeriva kelpkatusega.

Teine suurem restaureerimistööde läbiviimise aeg oli 1986.–1991. aasta, mil taas tehti tehnilise seisukorra uuringud, parandati pikihoone katusekatet, valati torni ülemine vahelagi ja kaeti torni katus uue plekiga ning võõbati vundamendi ülemine tsoon bituumeniga.

Kolmas restaureerimistööde periood hõlmas kooriruumi ja käärkambri ehitust ning viidi läbi 1994.–1998. aastast. Kooriruumi aknad, plokkaltar ja põrand restaureeriti, lisati vitraažaknad, maalingud konserveeriti, käärkamber restaureeriti tervikuna.

2000. a. tehti linnusealal arheoloogilisi kaevetöid, mille järgselt kaeti avatud struktuurid ajutise pultkatusega.

2013. a. ehitati pikihoonele uus katus ning rajati võlvidepealsele käiguteed.

Käesoleva restaureerimisprojektiga lõpevad 2003. ja 2012. a. sise- ja väliskrohvide ja -viimistluskihtide uurimistööd; käesoleva projekti põhirõhk on seega suunatud olemasolevate viimistluskihtide konserveerimisele ning sise- ja välisviimistluse uuendamisele.

1.3.2 Edasised uurimis- ja projekteerimistööd

Edasised vajalikud projekteerimistööd, mida käesolevas projektis ei käsitleta:

- kiriku ümbruse vertikaalprojekteerimise projekt, parkimisala ja teede planeerimine, piirdemüüride ja väravate restaureerimise projekt, linnuseala konserveerimise ja eksponeerimise kontseptsioon (eeldab geodeetilist alusplaani). Praegune linnusevaremete eksponeerimiseks paigaldatud (ajutine) varikatus risustab vaadet kiriku põhjaküljele ja tuleb eemaldada. Väljakaevatud linnuse keldriruumid tuleb sekundaarset pinnast täis ajada (liiv vms). Linnusemüüride pealt kaitsmise variandid: tinaplekk+murumätas, kaldega lubitsement-mört vms.
- infotahvlite paigaldamise projekt (info kiriku ja linnuseala kohta)
- torni projekt külastajatele avamise eesmärgil (eeldab tuleohutus- ja turvanõuete igakülgset arvestamist, torni vahelagede tugevuse kontrolli, valgustust, infotahvleid torni ajaloolisest kujust ja vaadetest, mis avanevad tornist jms)
- sisekujundusprojekt (pikihoone ja torni põrandate lahendus, mis eeldab täiendavaid uuringud ajalooliste põrandakihtide, algse kõrguse, samuti pikihoones paiknevate võimalike hauakambrite kohta), sisustuse projekt (pingid jm inventar)
- kiriku ja kirikuaia välisvalgustuse projekt
- kiriku kooriruumi digitaalselt rekonstrueeritud algset, keskaegset kujundust tutvustava infomaterjali eksponeerimise projekt

1.4 Muinsuskaitse eritingimused, nõuded ja piirangud

1.4.1 Üldosa

Pöide kirik kuulub ehitismälestisena kultuurimälestiste riiklikku registrisse, reg. nr 21058. Kaitse alla kuuluvad ka samal kinnistul asetsevad järgmised ehitismälestised:

— Pöide pastoraadi peahoone (reg. nr. 21060);
— Pöide pastoraadi piirdemüürid (reg. nr. 21061);
— Pöide linnuse säilmed (reg. nr. 21059);
— Pöide kirikuaed (reg. nr. 4156).

Naabruses asub Pöide-Levala munakivitee (reg. nr. 27287).

Kirikus on hulgaliselt kaitsealuseid kunstimälestisi (hauakivid, epitaafid jm); lähiümbruses on arheoloogiamälestisi (ordulinnuse kultuurikiht, kultusekivi).

1.4.2 Muinsuskaitse eritingimused

Hoonele on koostatud muinsuskaitse eritingimused, mis on võetud aluseks ehitusprojekti koostamisel (*Pöide kirik. Muinsuskaitse eritingimused.* Koostaja: J. Kilumets. Rändmeister OÜ, 2007. Kooskõlastus nr. 7032, 04.06.2007).

Selguse huvides on käesolevas projektis kasutatud avade, detailide jm ehitusosade märkimiseks samu tähiseid, mis eelnevalt koostatud muinsuskaitse eritingimustes.

Kokkuvõte 2007. a. koostatud muinsuskaitse eritingimustest:

<u>1. Põhiplaan ja kavatis</u>

1.1 Kiriku põhiplaanilise ulatuse muutmine on keelatud.

1.2 Ainus lubatud mahuline muutus vt. p. 13. katus ja tornikiiver.

<u>2. Kirikuaed, linnus, ümbritsev maapind, haljastus</u>

2.1 Korrastada/taastada kirikuaia piiretena käsitletavad ajaloolised kiviaiad, samuti väravapostid. Tööde osaline alus: Pöide kirikuaed. Planeeringuprojekt. OÜ Gromaticus, 2008. Markeerida kirikust edelas asunud värava kivipostid.

2.2 Koostada kiriku ümbruse vertikaalplaneeringu projekt sh kirikut ümbritseva horisontaalse hüdroisolatsiooni lahendus. Tugineda varasematele uurimis- ja projekteerimistöödele: sh Pöide kiriku väljakaevatud varemete ümbruse vertikaalplaneerimine. OÜ H. Uuetalu, 2001.

2.3 Pinnase planeerimisel ja kiviaedade taastamisel tagada vastav järelevalve — raidkivide leidmise potensiaal on suur.

2.4 Pinnasetöödel tagada kirikuga ristuvate, sekundaarsete müüride (1 lääne- ja 4 lõunaküljel) säilivus.

2.5 Viia lõoule varemeteala korrastamine, olemasolevaid probleeme arvestades uusi avasid mitte teostada.

2.6 Enne konserveerimistööde jätkamist vaadata läbi varemete katustamislahenduse projektdokumentatsioon (märksõnad: erikujulised katuse-pinnad; põhjaseina, portaali ja romaani akna eksponeerimistingimused.

2.7 Avada puudega varjatud vaade kiriku põhjaküljele ja linnusealale.

2.8 Kirikuaias paiknev hauaplaat teisaldada ja eksponeerida tornivõlvikus.

2.9 Linnuse territooriumile paigaldada infotahvel linnuse põhiplaani ja selgitava tekstiga (praegune olukord on äärmiselt vähekõnekas).

<u>3. Sokkel, seinad, fassaadidetailid</u>

3.1 Kõik nurgakvaadrid, sokliliist, karniisiplokid ning raidkivi- ja tellisdetailid D1-D4 konserveerida, krohvimisel eksponeerida. Kahjustustega kvaadrid proteesida konstruktiivse vajaduse korral, varasemad kvaadrite asendused (torni loodenurk) säilitada.

3.2 Soklil, aknaalustel ja uuringutsoonides lubatud varisenud, avatud või destruktiivse müüritise taastamine ajaloolise kontuurini. Materjal: originaalile lähedase pinnaga dolomiit (linnuse kaevetöödel kogutud kivid).

3.3 Aknaniššide põhjade ajalooline lahendus selgitada uuringutega (niššid vt. p. 10).

3.4 Telliste asendamisel kasutada originaalile vastava formaadiga käsitsivormitud telliseid.

3.5 Tõmbankrute plaadid ja torni nurgaklambrid konserveerida. Tõmbide süvistatud vastuslatid kooriruumi fassaadil ja silikaattellisparandused samas tsoonis katta krohviga.

<u>4. Väliskrohv ja –viimistlus</u>

4.1 Järgneva tegevuse üldisel planeerimisel juhinduda 2003. a. sissejuhatavate uuringute ja katsete aruandes esitatud tegevuskavast.

4.2 Põhiosas kuuluvad olemasolevad krohvid säilitamisele ja konserveerimisele, krohvi eemaldamine lubatud üksnes uuringutega põhjendatud juhtudel.

4.3 Fassaadikrohv ja –viimistlus üldjuhul taastatakse, konkreetsete tsoonide paranduste ulatus ja käekiri määratakse uuringute põhjal koostatud projektiga.

4.4 Krohviparandustel lubatud kasutada õhktahkuvat või hüdraulilist lubimörti, värvimisel lubivärvi.

4.5 Raidkividetaile ei krohvita. Aknaniššide tellisnurkade eksponeerimine on lubatud lõunaseina avadel A2–A4, kus krohv on valdavalt varisenud.

4.6 Käärkambri seinu ei krohvita, lubatud on vuukide täitmine.

4.7 Markeeritavad sõlmed: 1) kõik kiriku pikendamise ja kõrgendamisega seotud ühemõtteliselt tõlgendatavad ehitusjärkude liitekohad; b) romaani kiriku aknaniššide säilinud kontuurid.

<u>5. Peaportaal</u>

5.1 Teostada portaali säilivuse, seisukorra ja kahjustuste kaardistamine.

5.2 Portaali originaaltsoonid konserveerida.

5.3 Juhuslikud ja ebastabiilsed kiviparandused lubatud eemaldada.

5.4 Portaalidetailide rekonstrueerimine, samuti neutraalsed kiviparandused lubatud üksnes konstruktiivse vajaduse korral (nt. idapoolne sokkel). Muudel juhtudel säilitada kadude tsoonid muutusteta.

5.5 Viimistluste säilitamine otsustatakse uuringutega.

5.6 Hingetapid nii portaali välis- kui siseküljel lubatud eemaldada, konserveerida ja taaspaigaldada.

5.7 Läve situatsioon säilitada.

5.8 Niši varisenud tellismüüritis taastada, kasutades originaaltelliste mõõtudele vastavat käsitsivormitud tellist. Riivpalgi pesa taastada.

6. Välisuks

6.1 Uks säilitada asukohal, restaureerida.

6.2 Värvilahendus: järgida ajaloolisi sise- ja väliskülje toone; lubatud värvitüüp: linaõlivärv.

6.3 Metalldetailid konserveerida, alumine oskamatult remonditud hingelatt lubatud taastada laudisesse lõigatud jälje põhjal.

6.4 Lubatud paigaldada karplukk ja ühte uksepoolt allosas fikseeriv riiv.

6.5 Alumise (puuduva) valtsi ehk ukse tiheduse küsimus lahendada koos läänevõlviku põranda taastamisega.

6.6 Lubatud paigaldada tuulutusvõre — paiknemine ja kujundus lahendada projektiga.

7. Põhjaportaal

7.1 Teostada portaali säilivuse, seisukorra ja kahjustuste kaardistamine.

7.2 Portaali originaaltsoonid konserveerida.

7.3 Lubatud nihkunud plokkide asendi taastamine.

7.4 Seoses ukse paigaldamisega lubatud läänepoolse palendi puuduva ploki rekonstrueerimine.

7.5 Portaalikilbi müüritis konserveerida: vuukide täitmisel järgida mördi ajaloolist koostist ja värvitooni; mitte krohvida.

7.6 Lubatud portaalikilbi ülaosa tasandav parandus mahus, mis võimaldab pliiplekist katte paigaldamist

7.7 Paigaldada kahel hingel sisse avanev uks, sulus — riivpalk. Ukse konstruktiivse ja kujundusliku lahenduse eeskuju — Eesti keskaegsed uksed (Põide kirik. Välisviimistluse eskiisprojekt. R. Projekt, 1990.

7.8 Romaani portaali niši kontuurid interjööris eksponeerida, gooti portaaliniši varisenud nurk taastada, uksega seotud juurdelao katke lubatud eemaldada.

7.9 Niši ulatuses välja puhastada (vajadusel taastada) ja eksponeerida gooti portaali aegne, lävekiviga seotud põrandasituatsioon.

7.10 Tuulutusvõre paigaldamine on põhimõtteliselt lubatud, minimaalselt vajaliku kahe hingetapi asukohad määrata täiendava uuringuga, võre kujundus projektiga.

8. Lõunaportaal

8.1 Portaal ja kilp konserveerida: vuukide täitmisel järgida iseloomulikku kivikiilude kasutamist ning mördi ajaloolist koostist ja värvitooni. Portaalikilpi mitte krohvida.

8.2 Portaalikilbi ülaosas lubatud müüriparandus kuni ajaloolise kõrgus-jooneni. Kasutada originaalkivile lähedast dolomiiti kiriku varudest. kilbi horisontaalne aste katta tinaplekist veeliistuga.

8.3 Täitemüüritise välimise kihi välja vajunud ja ebastabiilne osa taastada olemasoleva materjaliga.

8.4 Portaaliniši gabariidid interjööris markeerida loetavalt.

9. Romaani kiriku aknaavad

9.1 Teostada viimistlusuuringud X1 täitemüüritise krohvil nii sees kui väljas.

9.2 Eeldusel, et krohvil ei esine olulise ajaloolise väärtusega viimistlusi, lubada täitemüüritise eemaldamine ava välisküljel.

9.3 Avamise jätkamine (lõpetamine) ja võimaliku avatäite lahendus otsustada esimese etapi tulemuste põhjal.

9.4 Algkiriku ülejäänud aknanišŝide X2, X3, X4, X5 palendinurgad markeerida nii sise- kui väliskrohvimisel lõikudes, mis on ühemõtteliselt tuvastatavad.

10. Gooti kiriku aknad ja avatäited

10.1 Koorivõlviku aknad ja vitraažid (A1, A2) säilitada.

10.2 Kõikide akende originaalraidkivid ja –tellised konserveerida.

10.3 Kõik raidkivi- ja tellispiidad (A3–A8) taastada või proteesida vitraažide paigaldamiseks vajalikus ulatuses. Asenduskivi: Kaarma dolomiit, käsitsivormitud tellis.

10.4 Ehisraamistikud (A3–A5) mõõdistada ja säilitada praeguses ulatuses (mitte rekonstrueerida); kaareosade avatäited kavandada vastavalt säilinud situatsioonile.

10.5 Nõuded avatäidetele A3–A8: a) Pliiklaasimine ajaloolisesse valtsi; b) Klaasitahvlite kinnitused: mitteroostetavast terasest latid ja tuulevardad paigaldada võimalikult ajaloolistesse kinnituskohtadesse, vajadusel piidakivide vuukidesse; c) Kujundamisel järgida akende arhitektuurset gradatsiooni.

10.6 Aknanišŝide originaaltellised konserveerida, purunenud või puuduvad tellised asendada originaalile vastavas mõõdus käsitsivormitud tellistega. Telliste suhe krohviga vt. p. 4. Nišŝide alused taastada eelnevalt uuringutega tuvastatud ajaloolises lahenduses.

10.7 Ümarakent A9 mitte avada. Argumendid: ehisraamistiku vähene säilivus ja piidakivide võimalik ebastabiilsus. Raidraam eksponeerida, täitemüüritise välispind konserveerida/parandada. Akna kontuur interjööris markeerida ning täitemüüritis eristada krohvi faktuuriga.

10.8 A10: raidraam konserveerida. Vältimaks originaalvaltsis pliiklaasimisega kaasnevat raidkivide suuremahulist proteesimist, paigaldada raidraami välisküljele separaatne piidata puitraamis klaas.

11. Torni avad (v.a. võlvik)

11.1 Kõikide avade algsed tellis- ja raidkivipinnad konserveerida.

11.2 Avade alused: L4, L12, L13 — taastada; L9–L11 ja L14–L16 juhuslik materjal lubatud asendada; ülejäänud avade alused konserveerida.

11.3 Silluskaared: L2, L3, L7 — taastada, kasutada originaalile vastavat materjali.

11.4 Kõik avade tellisraamistused fassaadil puhastada välja.

11.5 Täitemüüritised: ebastabiilsed L1 ja L6 ning avariiline L7 lubatud demonteerida. Taastamine/mittetaastamine otsustada täiendavalt. L5 täidis säilitada.

11.6 Avatäited: L9–L16 (kella- ja vaatekorrus) paigaldada ruumi poole avanevad piitadega luugid; L4 — paigaldada ohutusnõuetele vastav piire ja metallraamis linnutõkkevõrk; L8 — paigaldada riivpalgiga suletav luuk; L2, L3 — paigaldada metallraamis ohutus- ja linnutõkkevõrk.

11.7 UA2: palendi krohv konserveerida, avatäide paigaldada vaid juhul kui see on tuleohutusnõuete seisukohalt vältimatu.

<u>12. Muud avad</u>

12.1 X6: täitemüüritis säilitada. Interjööri krohvimisel markeerida ava gabariidid ning eristada täitemüüritis ümbritsevast seinapinnast krohvi faktuuriga.

12.2 X7: täitemüüritis taastada. Ava läänepoolsel küljel markeerida romaani kabeli kagunurk järgitavas ulatuses. Täitemüüritise pind eristada ümbritsevast fassaadipinnast krohvi faktuuriga.

12.3 X8: täitemüüritis taastada. Interjööri krohvimisel markeerida ava gabariidid.

12.4 L17, L18: avade piirded konserveerida, tellisraamistus eksponeerida; L17 alus taastada. Paigaldada lukustatavad luugid.

12.5 A11, A12: tellisraamistus konserveerida. Lindude probleemi korral paigaldada puitraamis tõkkevõrgud.

12.6 L19: tellisraamistus konserveerida ja eksponeerida. Paigaldada luuk olemasolevasse piita. Kellarõdu tarinduse markeerimine otsustada täiendavate uuringutega viilu välisküljel.

<u>13. Katus ja tornikiiver</u>

13.1 Kiriku katuse restaureerimistööde aluseks on kehtiv põhiprojekt (Pöide kirik. Katuse restaureerimisprojekt. OÜ Rändmeister, 2004.). Lisaks projekteerida ja paigaldada piksekaitse.

13.2 Olemasoleva tornikatuse säilitamise ja remontimise korral katuse kuju mitte muuta. Lubatud kattematerjal: tsingitud (ja värvitud) terasplekk.

13.3 Torni katus on lubatud lammutada. Tornikiiver on lubatud rekonstrueerida 1940. a. eelsel kujul. Tarinduse ja vormi projekteerimisel võtta kontrollituna aluseks 1960. a. lahendus (Pöide kiriku projektülesanne. TRT, 1960). Järjepidevusest tulenevalt katta tornikiiver tõrvatud kimmidega. Paigaldada piksekaitse.

13.4 Ajaloolise tornikiivri tipu elemendid — kuul ja tuulelipp — taastada.

Kuuli diameeter 50 cm (1960. a. andmed), tuulelipu üldise kujunduse aluseks võtta J. Naha skits (Muinsuskaitseameti arhiiv.

14. Võlvid ja võlvitoed

14.1 Pikihoone ja tornialuse võlvisiilude ning telliskaarte müüritis konserveerida, vajadusel vuukide ja pragude täitmine. purunenud tellised asendada originaaltelliste mõõtudele vastavate käsitsivormitud tellistega.

14.2 Võlvistiku raiddetailid konserveerida.

14.3 Ruumikliimat arvestades säilitada esialgu kõik avad võlvisiiludes. Mattunud originaalavad välja puhastada.

14.4 Võlvistiku viimistlus vt. p. 16.

15. Seinad interjööris, võidukaar, tornikaar, niššid

15.1 Ehitusarheoloogilised avamised seintes kinni müürida.

15.2 Avade täitemüüritiste käsitlused vt. p. 7–10, 12.

15.3 Kunagiste sisustuselementidega seotud avad võidu- ja tornikaarel säilitada. Selgitada pikihoone lõunaseina talapesade positsioon — nende lõpliku vormistamise otsus vastavalt uuringu tulemusele.

15.4 Niššide raidkivi- ja tellisosad konserveerida, viimistluslahendus kontrollida täiendava uuringuga.

16. Sisekrohv ja –viimistlus, maalingud

16.1 Läbi vaadata kooriruumi viimistluskontseptsioon (Pöide kiriku siseviimistluse sondeerimistööde aruanne. KAR Grupp, 1994; Pöide kiriku kooriruumi maalingute konserveerimis-uurimistööde aruanne. KAR Grupp, 1995), hinnata tulemused ja säilivus. Võimalike paranduste/muudatuste vajadus otsustada ekspertiisi põhjal.

16.2 Pikihoone ja tornivõlviku krohvid ja viimistlused uurida ja kaardistada kogu ulatuses seisukorra, ajaloolise stratigraafia ning maalingute aspektist.

16.3 Uuringute põhjal koostada kogu keskaegset interjööri (seinad, võlvid, raiddetailid) hõlmav krohvi ja viimistluse konserveerimise-restaureerimise kontseptsioon ja projekt.

16.4 Uuringuteni kuuluvad olemasolevad krohvid ja viimistluskihid säilitamisele.

16.5 Täitemüüritise krohvimine vt. p. 7–10, 12.

17. Põrandad

17.1 Kooriruumi põrand säilitada muutusteta; taastada ekspositsioonikambri selgitav legend.

17.2 Pikihoones ja tornivõlvikus täpsustada uuringutega ajalooliste põrandate stratigraafia ja kõrgusmärgid.

17.3 Betoonpõrandate osas selgitada uuringutega varasema põrandamaterjali võimalik säilivus betooni all.

17.4 Pikihoone keskkäigu, pingiplokkide aluse tsooni ja tornivõlviku põrandate taastamise lõplikud kõrgusmärgid anda uuringute põhjal. Säilitada kaheastmeline vahe kooriruumi põranda suhtes.

17.5 Põhjaportaali niši ulatuses välja puhastada (vajadusel taastada) ja eksponeerida portaali aegne, lävekiviga seotud põrandasituatsioon (Saaremaal Pöide kirikus teostatud väliuurimistööd. Kd I. TRT, 1962). Välistatud ei ole uuringute (restaureerimise käigus ilmnevate terviklike keskaegsete põrandatsoonide eksponeerimine mujal.

17.6 Betoonpõranda säilitamine otsustada uuringute põhjal, säilitamisulatus määrata projektiga. Keelatud on betooni kui ehitusloolise dokumendi täielik lammutamine.

17.7 Pikihoone ja läänevõlviku põranda taastamisel kasutada dolomiiti: materjali kuju, mõõdud ja pinnakäsitlus, samuti põranda muster ja suhe taastatava pingistikuga määrata projektiga.

17.8 Ilmnevad hauakambrid plaanistada. Katmislahendus sõltub kambrite suhtest põrandapinnaga ja määratakse projektiga.

<u>18. Vahesein</u>

18.1 Vahesein säilitada; krohv säilitada ja parandada, viimistlus vastavalt varaseimale ajaloolisele kihile.

18.2 Uks lubatud taastada, tahvlijaotus määrata ajalooliste fotode põhjal.

18.3 Aknad säilitada, puhastada.

18.4 Orelivääri tarinduse jäljed säilitada, talapesad eksponeerida. Vääri taastamine vt. p. 22.

<u>19. Käärkamber</u>

19.1 Lubatud fassaadiviimistlus: täidetud vuukidega müüritis (mitte krohvida).

19.2 Katuse, avatäidete ja interjööri situatsioon säilitada, lubatud telliste konserveerimine ja hooldustööd.

<u>20. Müüritrepp, võlvipealne ja torniruumid</u>

20.1 Müüritrepi purunenud astmekivid proteesida; portaali, seinte ja võlvi osas situatsioon säilitada.

20.2 Võlvipealse käigutee ja trepp säilitada olemasolevas ulatuses, remontida.

20.3 Torni vahelaed, põrandad ja trepp säilitada olemasolevas ulatuses ja tarinduses. Teostada tehniline uuring, vajadusel tarindid remontida.

20.4 Pääs katusealusele korrusele sulgeda, jätta teenindusluuk. II korrusel olevad metalltalad eemaldada.

20.5 Välja ehitamata ajaloolist vahelage mitte taastada.

20.6 Torni I korruse seinte krohv säilitada, konserveerida.

20.7 II korrusele lubatud paigaldada kellatool.

20.8 Turistide lubamine võlvipealsele ja torni kooskõlastada Päästeametiga.

21. Sisustus ja kunstimälestised

21.1 Plokkaltar säilitada, viimistluse parandamisel järgida praegusut lahendust.

21.2 Ristimiskivi vaagen puhastada ja konserveerida. Sobivuse korral Saaremaa Muuseumis säilitatava jalaga komplekt taastada. Vastasel juhul valmistada dolomiidist sokkel (jalg) ristimiskivi eksponeerimiseks ja kasutamiseks.

21.3 Hauaplaadid ja fragmendid kooriruumi põrandas säilitada praegustel asukohtadel, inventeerida, plaanistada, koostada legend.

21.4 Dolomiidist epitaafid lõunaseinal säilitada asukohal, puhastada, konserveerida; porsunud kinnitusdetailid lubatud asendada.

21.5 Hauaplaatide ja raidkivide ekspositsioon tornivõlvikus säilitada.

21.6 Kirikuaias asuv hauaplaadi fragment ning tekstiga kivi käärkambris konserveerida ja eksponeerida läänevõlvikus sarnaselt teiste plaatidega.

21.7 Pingistiku alustala konserveerida ja eksponeerida algsel kohal isoleerituna kivipindadest.

21.8 Kantsli kõlaräästa kinnitushaak ja oreliväänri sammaste soklikivid säilitada asukohal.

22. Uus sisustus

22.1 Uued sisustuselemendid ei tohi varjata ega nende paigaldamine kahjustada ajalooliselt väärtuslikke tarindeid ja detaile.

22.2 Plokkaltar ja ristimiskivi vt. p. 21.

22.3 Pingistiku ja oreliväänri tsoonid ei tohi ületada vastavaid ajaloolisi gabariite.

22.4 Mittesakraalse tegevusega seotud sisustuselemendid koondada võimalikult tornivõlvikusse.

22.5 Õppida meie ajalooliselt väärtuslike sakraalinterjööride taastamise kogemustest.

23. Elekter ja küte

23.1 Üldprintsiibina on elektriseadmete ja –juhtmestiku paigaldamisel keelatud kahjustada ajaloolist substantsi s.o. olemasolevat krohvi, müürikive, vuugistikku ning kultuurikihti.

23.2 Konkreetsete probleemide lahendused (nt. läbiviik käärkambrisse ja torni, kooriruum tervikuna) otsustada elektriosa projekteerimise käigus. Projekteerimisse kaasata vastutav kunstiajaloolane.

23.3 Küttekehade kinnitamine ajaloolistele pindadele on keelatud, alternatiiv — uued tarindid ja sisustuselemendid (nt. pingistik).

23.4 Korraldada kiriku tuulutamine, milleks koostada kogudusele vastav juhend.

1.4.3 Säilitatavate kultuuriväärtuslike detailide nimekiri

Kõik kultuuriväärtuslikud konstruktsioonid ja detailid on märgitud joonistele A-1…A-9. Konserveerimis- ja ehitustööde käigus peab olema tagatud loetletud konstruktsioonide ja detailide säilimine kahjustusteta.

Fassaadid

1. Torni, pikihoone ja käärkambri kivikehand, olemasolev väliskrohv (v.a. 20. saj. tsementi sisaldavad parandused) viimistluskihtidega;
2. Nurgakvaadrid;
3. Akna-, ukse- ja luugiavade raidkivi- ja tellisraamistikud ning –sillused;
4. Kooriruumi profileeritud sokliliist;
5. Karniisiplokid;
6. Tellisrist lääneseinal;
7. Peaportaal raiddetailidega;
8. Põhjaportaal raiddetailidega, lävekivi, riivpalgi pesad;
9. Lõunaportaal raiddetailidega;
10. Veesüliti, veesüliti katke, lavatooriumi renniots;
11. Avade katked;
12. Välisuks VU-1, hingetapid;
13. Aknad A-1, A-2, A-13 koos suluste ja vitraažidega;
14. Torni tõmbankrute plaadid lõuna- ja põhjaseinal;

Interjöör

15. Olemasolevad krohvikihid (v.a. 20. saj. tsementi sisaldavad parandused) viimistlus- ja maalingukihtidega;
16. Ristvõlvid koos raiddetailidega (roided, konsoolid jms);
17. Paeastmetega müüritrepp, silindervõlv;
18. Võidukaar raiddetailidega;
19. Kooriruumi nišid ja nende raiddetailid;
20. Kooriruumi põrand, ekspositsioonikamber, trepiastmed, hauaplaadid tõsterõngastega;
21. Pikihoone keskaegse põranda dolomiitplaadid;
22. Plokkaltar;
23. Sisesein akna- ja ukseavadega;
24. Siseseina aknad A-14, A-15;
25. Käärkambri uks U-2 sulustega ja lääneseina luuk;
26. Müüritrepi uks U-1 sulustega
27. Siseportaalid;
28. Tornivõlvikus eksponeeritavad raiddetailid.

1.4.4 Nõuded ja piirangud

Pöide Maarja kirik kuulub riikliku kaitse all olevate ehitismälestiste hulka (reg. nr 21058), mis kohustab kõikide ümberehitus- ja remonttööde puhul käituma nendega vastavalt Eesti Vabariigi muinsuskaitse seadusele. Igasuguste konserveerimis- ja restaureerimistööde esmaeesmärk on tagada objekti maksimaalne säilimine võimalikult väheste lisanditega.

Kiriku mistahes osa kohta tehtavad uuringud ja projektid, sh arhitektuursed-, konstruktiivsed-, sisekujundus-, eriosade vms projektid tellida selleks vastavat tegevusluba omavalt ettevõttelt; projektid kooskõlastada Muinsuskaitseametiga.

Lammutus- ja ehitustööd tuleb läbi viia muinsuskaitselise järelevalve tingimustes vastavat tegevusluba omava firma poolt, tööde läbiviimisel tuleb erilist tähelepanu pöörata muinsuskaitse eritingimustes mainitud säilitamisele kuuluvatele elementidele ja konstruktsioonidele. Järelevalve teostaja jälgib restaureerimis- ja remonttööde kulgu ning vastavust esitatud nõudmistele, töö lõppedes esitab teostatud tööde kohta aruande.

2 Arhitektuur

2.1 Asendiplaan

2.1.1 Olemasolev olukord

2.1.1.1 Paiknemine

Pöide Maarja kirik asub Saare maakonnas, Pöide vallas, Pöide-Levala tee (tee nr. 6340029, reg. nr. 27287) ääres. Munakivisillutisega tee kulgeb Kuressaare-Orissaare maanteelt u 420 m pikkuselt läbi Levala küla kirikukompleksi suunas, ning moodustab sellega ühtse terviku.

Kirik on rajatud vanasse kultusekohta, millest annab aimu lähedal paiknev kultusekivi (arheoloogiamälestis, reg. nr. 12642) kirikuhoonest u 200 m kagusuunas.

Kiriku ristkülikukujuline põhimaht (13,4 x 53,2 x 25 m) kulgeb lääne–ida suunaliselt (väikese kõrvalekaldega edela-kirde suunal), kirdenurgas on eenduv käärkamber.

Kirikust lõuna pool paiknes kirikuaed (reg. nr. 4156). Kirikust põhja poole rajati aastatel 13. saj. keskel linnus (reg. nr. 21059, 12643) u 45 x 60 m suurusel maa-alal, mille osaliselt väljakaevatud varemed on kaetud ajutise katusega.

Pöide kalmistu asetseb kirikust umbes 900 m edela suunas; selle dominendiks on 1791. a. ehitatud G. W. von Aderkasi kabel (reg. nr. 21057).

Asendiplaani vt. leht AS-1. Asendiplaani aluseks on 1974. a. mõõdistatud alusplaan.

2.1.1.2 Olemasolev hoonestus

Kirikuhoonest lääne pool asetseb pastoraat ja seda ümbritsevad pae- ja maakiviaiad (reg. nr. 21060, 21061). Sissesõidutee ääres paikneb paekivist abihoone.

Kiriku põhjaküljel paikneb 13. saj keskel rajatud linnuse hoonestus, mille lõunatiib piirneb vahetult kirikuhoonega. Linnus sai kannatada juba 14. sajandi keskel; säilinud on vaid maa-alused konstruktsioonid ja vähesel määral maapealseid müürikatkeid. Linnuse lõunatiiva hoonestus fikseeriti arheoloogiliste välja-kaevamistega 2000. a., mille järel need kaeti ajutise katusekonstruktsiooniga.

Antud projektis käsitletakse ainult Pöide kirikuhoonet. Restaureerimistööde käigus hoone kuju ja suurust ei muudeta.

2.1.1.3 Olemasolev reljeef

Pöide ümbrusele on iseloomulik paks moreenkate, miles esineb mitmemeetrise läbimõõduga plaatjaid dolomiidipangaseid. Kirik paikneb lamedal moreenkühmustikul. Vahetult kiriku idaserva ja linnuseala põhjaotsast tekib maapinna järsk langus kirde suunas. Hoone vahetu ümbruse kõrgusmärgid paiknevad vahemikus +10.39 kuni +12.22. Väljakaevatud linnusevaremete fikseerimisel on kiriku põhjaportaali lävekivi absoluutkõrgusmärgiks mõõdetud +10.25.

2.1.1.4 Olemasolev haljastus

Ajaloolistelt fotodelt nähtub, et kiriku ümbrus on olnud suhteliselt lage mõne suurema põlispuuga või põõsagrupiga. Viimase poole sajandi jooksul on kiriku ja pastoraadi ümbruse haljastust minimaalselt kujundatud ja piiratud ning juhusliku tekkega taimestik häirib vaadet kirikule ja pastoraadile. Veel kümmekond aastat tagasi oli tugevasti võsastunud endine linnuseala, kust nüüd on jõudumööda, peamiselt talgukorras võsa lõigatud. Pastoraati ümbritsevad kõrged põlispuud.

Antud projektiga haljastust ei käsitleta.

2.1.1.5 Olemasolev teedevõrk

Hoonele lähenemine toimub lõunasuunast kruusakattega teelt, mis lõpeb pastoraadi ja kiriku vahelisel lagendikul. Kirikut ümbritsevad teed ja jalgrajad on rohtunud. Antud projektiga teedevõrku ei muudeta.

2.1.1.6 Olemasolevad piirded

Kirikuaed oli ümbritsetud madalate maa- ja paekivist aedadega. Säilinud kiviaialõigud ümbritsevad kirikuaeda ida- (u 15 m kaugusel kirikust) ja lõunaküljelt (u 80 m kaugusel maantee ääres, reg. nr. 4156). Juurdepääsutee on lõunast, kiriku ja pastoraadi vahelt, ning sissesõidutee ääres on samuti lõiguti säilinud vana kiviaeda. Kivist postidega värav kirikuaeda paiknes kiriku ja pastoraadi vahelises piirdemüüris torni edelanurga läheduses. Väravakoht on alles, postidest on säilinud kaks dolomiidist kuuli kirikus. Lihtsam puitvärav asetses kirikust loodes, suurem värav sissesõiduteel kirikust edelas. Puitväravad on hävinenud, kiviaiad enamuses varisenud või mattunud.

Vanad kiviaiad kuuluvad perspektiivselt taastamisele, kuid neid ei käsitleta selles projektis. Uusi piirdeid ei ole projekteeritud.

2.1.2 Vertikaalplaneerimine

Antud projekti hõlmavate restaureerimistöödega hoone kuju ja suurust ei muudeta. Olemasoleva ehitise absoluutkõrgusmärgid jäävad samaks. Säilitatakse hoone sokli kõrgus 40-60 cm maapinnast. Eelnevate uurimis- ja ehitustööde ajal pinnase teisaldamise käigus tekkinud maapinnakonarused, augud ja vallid, mis kohati juhivad vee hoone suunas, tasandatakse.

Sadeveed nõrguvad loomulikul teel hoone katuselt; sadevetesüsteemi ei ole ette nähtud välja ehitada. Seetõttu tuleb maapinda planeerides juhtida liigne vesi hoonest eemale. Hoone ümber rajatakse horisontaalse hüdroisolatsiooniga sillutisriba, mis kaetakse pinnasega ja väikesefraktsioonilise paekillustikuga. Täpsemalt vt. p. 2.3.3.2

Kiriku põhjaküljel paiknevate linnusevaremete konserveerimine ja eksponeerimine lahendatakse omaette projektiga; käesolevas projektis vertikaal-planeerimist v.a. sillutisriba hoone ümber, ei käsitleta.

2.2 Arhitektuurne üldlahendus

2.2.1 Hoone üldandmed

Gabariidid: 13,4 x 53,2 x 25 (torni kiviosa) m
Funktsioon vastavalt ehitise kasutamise otstarbe loetelule: 12721 (kirik)

2.2.2 Hoone tehnilised näitajad

Kinnistu suurus	40,61 ha
Ehitise alune pind	741,4 m^2
Ehitise suletud netopind	1220 m^2
Ehitise maht	10340 m^3
Ehitise korruselisus	1 (tornis 3)

2.2.3 Tuleohutusnõuded

Hoone kasutusviis: IV (kirik)
Kasutusotstarve: 12721 (kirik)
Tuleohutusklass: TP2

Hoone on jagatud olemasolevate konstruktsioonide baasil kolmeks tuletõkkesektsiooniks:

- esimene korrus ja müüritrepp;
- pikihoone pööning;
- torni 2. ja 3. korrus.

Tuletõkkekonstruktsioonide tulepüsivus vastab nõuetele. Torniosa on eraldatud pikihoone pööningust tuletõkkeuksega EI30. Pikihoone pööning on eraldatud müüritrepikäigust tuletõkkeuksega EI30. Ustel kasutatakse nõuete-kohaseid sulgureid.

Kuna tegemist on spetsiifilise funktsiooniga hoonega (kirik), mis on ehitatud enne viidatud määruse jõustumist, siis vastavalt määrusele "Ehitisele ja selle osale esitatavad tuleohutusnõuded" § 40 lõige 1 on tagatud hoonest inimeste evakueerimine. Kirikuhoone esimesel korrusel on kaks väljapääsu otsepääsuga õue. Pikihoone pööningul ega tornis inimesi alaliselt ei viibi.

Korraldatavate kontsertide ajaks on ette nähtud paigaldada väljapääsude kohale väljapääsu markeeriv kleebis.

Pikihoone puitkandjatel katusekonstruktsioon on kaetud keraamilise katuse-kiviga. Katusekate (munk-nunn savikivi) vastab nõudele B_{ROOF}. Piksekaitsesüsteem projekteeritakse ja paigaldatakse pärast uue katuse valmimist 2014. a.

Kandekonstruktsioonidele tulepüsivusnõuet R ei esitata. Põrandad on betoonist, olemasolevad, nõuded puuduvad.

Hoones on töökorras küttekolle (kamin käärkambris), uusi küttekoldeid hoonesse ei ole ette nähtud. Hoone on kütmata.

2.2.4 Tervisekaitsenõuded

Keskkonnamõjud: hoone ja hoones toimuv tegevus ei kujuta ohtu ümbritsevale keskkonnale.

Jäätmekäitlus: hoones regulaarset olmeprügi ei teki. Kontsertide toimumise ajaks paigaldatakse ajutised prügikotid, mis ürituse lõppedes minema viiakse. Ehitusjäätmete käitlemine vt. p. 2.4.2.

Ruumide sisekliima: nõudeid ei esitata.

Ruumide heliisolatsioon: nõudeid ei esitata.

Kõikides ruumides on tagatud loomulik valgustus.

2.2.5 **Hoone ehitusetapid** (vt. ka Osa B, lisa 2.1)

Põide kiriku praegune kehand on kujunenud erinevate ehitusetappide tulemusel.

I

Uurijad on ühisel seisukohal, et vanimast, romaani algkirikust on säilinud pikiseinad, mis moodustavad praeguse lõuna- ja põhjafassaadi keskosa, seejuures olid algkiriku müürid praegustest oluliselt madalamad. Oletatavasti liitus sellega kitsam kooriruum. Sellest perioodist on säilinud kaks portaalikohta ning tuvastatud pikiseinte kuue aknaava allosad.

II

Järgmise ehitusperioodi tulemusena ehitati hilisema torni alus lihtsa kehandina vastu romaani algkiriku läänekülge, mis võis olla kaetud sirge lae või katuslaega. Juurdeehituse põrandapind võis asetseda pikihoone omast madalamal. Portaaliavad rajati nii põhja- kui lõunaküljele; ka ümaraken ja kolm teravkaarset akent läänevõlvikus pärinevad ilmselt sellest perioodist.

III

Nn. gooti ümberehitusperioodil lammutati kiriku varasem kooriruum ja läänesein; kirikule lisati pikihoonega sama lai uus kooriruum. Seinad kõrgenesid märgatavalt; kirik võlviti. Läänevõlviku lõunaseinas olnud portaalile lisati üks pikihoone põhjaseina. Romaani aknad müüriti kinni, samuti pikihoone lõunaportaal, torni põhjaportaal ja roosaken läänefassaadil. Ehitati uued aknad — kolme- ja kahejaoline kooriruumis, kolm lantsettakent pikihoones. Ehitustööde täpset järjestust ei olnud 2012. a. siseviimistluse uuringutega võimalik tuvastada.

IV

Torni kõrgendamise tingis tornialuse ruumi võlvimine, aga ka varasemast kõrgema pikihoone valmimine. 2012. a. siseviimistluse uuringutega on tuvastatav erinevate mörtide kasutamine, mis jagab torni ehitamise korruste kaupa kahte etappi, mille vahel ei pruukinud olla pikka intervalli.

V

Käärkamber on hiliseim kiriku kavatist muutev ehitus, mille täpset ehitusaega ei ole olnud võimalik seniste uuringutega öelda. Teada on fakt, et kooriruumist käärkambrisse viiv ukseava on kiviseina sisse murtud.

VI

17. -18. saj. toimusid ulatuslikud fassaadide krohvimistööd, mille käigus kaunistati akende ja uste avad seinapinnast eenduva krohviraamistusega. Kirik valgendati, interjöör kaunistati maalingutega.

VII

Viimane oluline lisand kiriku arhitektuurses kujunemises on 1852. a. ehitatud vahesein tornialuse võlviku ja pikihoone kahe ülejäänud võlvikute vahele, millega koos rajati orelirõdu (hävinud).

2.2.6 Hoone kirjeldus ja seisukord

2.2.6.1 Plaanilahendus

Pöide kirik on Lääne-Eesti ja saarestiku suurim ühelööviline sakraalhoone. Erinevatel ehitusetappidel kujunenud ristkülikukujuline ehituskehand koosneb neljast ühelaiusest ristvõlviga kaetud võlvikust, mis on põhiplaanilt ruudukujulised. Idapoolne võlvik moodustab koori, kaks keskmist täidavad rahvale määratud pikihoone ülesannet ja läänevõlvik on tornialuseks eesruumiks. Viimast eraldab pikihoonest sekundaarselt rajatud vahesein (kannab daatumit 1852). Kooriruum on pikihoonest eraldatud võidukaarega. Põhimahule liitub kirdenurgas hiljem rajatud käärkamber.

Sissepääsud kirikusse paiknevad tornivõlviku lõunaseinas ning pikihoone idavõlviku põhjaseinas.

Kooriruumi põhjaseinast kulgeb silindervõlviga kaetud paekivist müüritrepp võlvipealsele. Tornis oli (võlvi peal) algselt kolm kaitsekorrust. 1959-1960. aastatel jagati torn puit- ja betoonvahelagedega kaheks korruseks, lisandus katusealune korrus (torni pööning). Torni pääseb pikihoone võlvidepealselt pööningult. Tornis on puittrepid ja -redel.

Hoone plaanilahendust käesoleva projektiga ei muudeta.

2.2.6.2 Fassaadid

Kiriku dominandiks on massiivne läänetorn, mille telkkiiver ulatus enne hävimist 1940. a. tulekahjus tolleaegsete ajalehtede andmetel hinnanguliselt u 32 meetrini, tegelikkuses jäi ilmselt u 25,5 m kõrgusesse, s.o. proportsioonis 1:1 torni kiviosaga. Torni lõpetab 1960. a. paigaldatud ajutine madal plekiga kaetud kelpkatus. Pikihoonet katab kõrge viilkatus, mille restaureerimine on pooleli (2013. a.). Katusekate: keraamiline savikivi.

Paekivist hoonel on madal paekivist sokkel (v.a. tornikehandil), millel võib eristada kahesugust kujundust: pikihoone osas murdaste, kooriruumi osas raidkivist soklisimss. Gooti perioodil kujundati kirikul (sh tornil kogu kõrguses ja käärkambril) kvaadernurgad; fragmentaarselt on säilinud varasema romaani kiriku nurgaketid. Kiriku pikiseinad ja tornitüves lõpevad dolomiitplokkidest profiilkarniisiga.

Välisseinad on olnud krohvitud; raidkivi- ja tellisedetaile on läbi aegade käsitletud erinevalt. Krohvi säilivus on seinte kaupa väga erinev; suuremad lagunemised on lõunaseinal ja põhjaseina allosas.

Fassaadil on mitmeid tähelepanuväärseid raiddetaile: veesüliti kooriruumi lõunaseinas, veesüliti katke idaseinas, lavatooriumi renni ots lõunaseinas.

Hoone fassaadide kujundust ei muudeta; markeeritakse kinnimüüritud avad. Raiddetailid eksponeeritakse.

2.2.6.3 Avad, avatäited

Tornivõlviku lõunaseinas paikneb teravkaarne kaheastmeline raidportaal, milles paikneb diagonaallaudisega kahepoolne välisuks. Põhjaportaal pikihoone keskel on raidkivist ehisraamistikulise tümpanoniga; avatäide puudub. Portaalidel on mehaanilisi vigastusi, osa detaile puuduvad.

Romaaniaegsed avad on kinni laotud. Fasaadi ilmestavad kõrged ja kitsad gooti tellis- ja/või dolomiitpiitadega aknad. Neist kooriruumi kaks akent on restaureeritud ning vitraažidega varustatud. Teiste gooti akende kohta on koostatud restaureerimisprojekt. Praegu on aknaavad kaetud ajutiste puitkilpidega (A-3…A-4, A-6…A-8, A-10) või –akendega (A-5). Aknaavas A-10 paiknesid nüüdseks eemaldatud trellid.

Aknanišŝide servad on vormistatud tellisraamistusena. Avade servad on kohati väga lagunenud; tellistel ja kividel on mehaanilisi vigastusi ja kadusid.

Müüritrepil on väikeseid valgusavasid, mis on kaetud ajutise linnutõkkevõrguga (PVC võrk puitraamis).

Torni 1. korrusel asub kinnimüüritud ümmargune roosaken, mille raidraamistus on hävinenud; aken on paekiviga kinni müüritud. Torni ülakorrusel on mitmeid ümar- ja segmentkaarseid avasid, millel osadel on seestpoolt kinnitatavad luugid. Enamjaolt on avad lahtised. Avade servad on kohati väga lagunenud, osa on kinni müüritud.

Käesoleva projektiga lahendatakse puuduvad avatäied (v.a. gooti aknad). Avade ja avatäidete kohta vt. p. 2.3.4.6…2.3.4.9.

2.2.6.4 Interjöör

Interjööri üldpildi määravad ristvõlvid, mis moodustavad 2/3 ruumi kõrgusest. Kooriruumi võlv (kilpkaare, mõigasroided, päiskivi) toetub raiddekooriga nurgatugedele. Pikihoone tellistest kilpkaartega servjoonvõlvid toetuvad võlvikute nurkades raidkonsoolidele (idavõlvikus taim- ja maskdekooriga). Tellistest vööndkaar toetub massiivsetele raidkonsoolidele, mille alumise tsooni moodustavad taim- ja figuraaldekooriga konsoolid. Servjooned on rõhutatud krohviga ja kvaadermaalinguga, ka päisringid on krohvitud. Võlvid on üldjoontes heas seisukorras, pragusid on minimaalselt. Siiski esineb võlvikivide pragunemist ja telliste küllastumist niiskusest ja sooladest. Kohati on vuugid tühjenenud.

Võlvid ja seinapinnad on krohvitud, kuid ulatuslike niiskuskahjustuste tõttu kirikus on sisekrohvi säilinud hinnanguliselt u 60% ulatuses, kuid sellest on suur osa seinapinnalt lahti või muul viisil hävimisele määratud (pudedaks muutumine, kivistumine). Krohvi- ja kivipindadel vohab rohevetikas, niiskusrežiimi kõikumised on tekitanud sooldumisi. Kõige halvemini on säilinud tornivõlviku krohv, mis on suures osas hävinud.

Kooriruum on ülejäänud võlvikutest eraldatud raiddolomiidist võidukaarega. Kooriruumi seintes on mitmeid nišše, mõnedel raidraamistus. Kooriruumis tehti restaureerimistöid 1994-1995, mil avati ja eksponeeriti erinevate ajalooliste kihtide maalingud võlvil (roideimitatsioon jm) ning idaseinal (baldahhiin).

Nii välis- kui sisekrohvikihtide stratigraafilised uuringud tehti 2003. ja 2012. a., mil tuvastati mitmeid eri perioodidest pärit ajaloolisi krohvitüüpe ning maalinguid. Uuringute käigus kaardistati krohvikihtide tüübid, kahjustused ja säilinud viimistluskihid, sh maalingud.

Kooriruumi maalinguid on varasemalt sondeerinud KAR-Grupp 1994. a., peale mida kooriruumi krohvi- ja värvikihte restaureerimiste käigus uuendati. Koorivõlviku leht- ja lillmotiiviga päiskivi on krohviga modelleeritud.

Tornivõlvikul on telliskvaadreid imiteerivad kilpkaared. Võlviku tipus krohviga modelleeritud päiskivil ja teravselgsetel servjoontel on taime- ja lehemotiividega maalingud. Terve pikihoone ulatuses tuvastati väheseid maalingufragmente kilp- ja vööndkaartel, akende raamistuses ning ulatuslikumalt võlvipäistes ja servjoontel. Telliskvaadreid imiteeriv maaling on kantud kilpkaarte osas otse tellisele ning seda ääristab must joon. Servjoontele on maalitud laiad beežikaspruunid "roidekivid".

Pikihoone idavõlviku põhjaseina ülaosas, varasema romaani akna ülekrohvitud kihil tuvastati suurema kompositsiooni olemasolu, mille kuju väljaselgitamine vajab täiendavaid uuringuid. Sama seina allosas on säilinud ilmselt uusaegsed maalingukatked. Maalingukatkeid on ka idavõlviku lõunaseinal epitaafi ümbruses ja selle külgedel. Kooriruumi maalingud on rikkalikumad ja paremini säilinud, hõlmates gootiaegset maalingukihti (maalitud võlviroided ja kilpkaared, 8-tipulised tähed, põhjaseina roosakna katke) ja uusaegseid (marmoreering, altari baldahiini maaling) kihte. Ka päiskivil on polükroomiakatkeid. Maalingute seisukord on suhteliselt halb, v.a. gooti maalingud kooriruumis, mis on küllaltki kompaktsed.

Sisekrohv on ette nähtud säilitada ja teha krohviparandused, kui seinte niiskusrežiim seda võimaldab. Täpsemalt vt. p. 2.3.4.11.

Tornivõlviku aluse ruumi põrand on 2/3 ulatuses kaetud betooniga; läänepoolset osa katab liiv. Pikihoones leidub põrandakihte mitmest ehitusperioodist, osalt on säilinud ka keskaegseid dolomiidist põrandaplaate. Viimane kiht pikihoones on olnud betoon, v.a. lõunapoolse pingistiku alune, kus veel 1940. a. oli laudpõrand. Praegu on betoon säilinud vaid keskosas, mujal on muldpõrand.

Esialgu betoonpõrandad säilitatakse. Täpsemalt vt. p. 2.3.4.12.

2.2.6.5 Sisustus

Varaseimad teated kiriku sisustusest pärinevad 1792. a. visitatsiooniprotokollist. Kogu kooriruum ja osaliselt pikihoone põrandaalune oli jagatud hauakambriteks. Samas mainitakse hulgaliselt erinevaid (puidust) pinke. Rahvale mõeldud puitpingid kirikusaalis olid paigutatud pikiseinte äärde, jättes keskele küllalt laia vahekäigu.

Kirikus oli veel hoone eripära arvestades vajalikku atribuutikat: kantsel kõlaräästaga, loožid, köstri kantsel, puitfiguurid, oreliväär ja orel, kirikukellad, kroonlühtrid jms. Kogu sisustus mõne erandiga hävines kas 1940. a. tulekahjus või pärast seda, 1946. a. jooksul.

Algsetest matustest on säilinud mitmeid hauaplaate või nende fragmente, mis kuuluvad kunstimälestistena kaitse alla (kokku 14 tk., reg. nr.-d 27327—27335, 28548, 6263—6266). Lisaks on kirikus säilinud raiddekoori: bareljeefe ja epitaafe (reg. nr.-d 6261, 6262, 6268) ning ristimiskivi (reg. nr. 6267). Rüüstamisest päästetud kantsli alussambaks olnud Peetruse kuju asub Saaremaa muuseumis, kus hoitakse ka ristimisvaagna jalga.

Kirikus on säilinud plokkaltar taastatud kujul. Torni 1. korruse ruumis eksponeeritakse raidkivide fragmente (osaliselt pärit Valjala kirikust).

Sisustust käesolevas projektis ei käsitleta. Ristimiskivi tuleb sobitada olemasolevale muuseumis hoitud jalale; vajadusel proteesida puuduolevad osad või valmistada uus Saaremaa dolomiidist jalg. Restaureeritud ristimiskivi paigutada kooriruumi, plokkaltari ja lõunaseina vahele.

2.3 Konserveerimis- ja ehitustööd

2.3.1 Konserveerimistööde üldosa

Käesolevas projektis on lähtekohaks konserveeriv meetod; planeeritud töid nimetatakse eelkõige *konserveerimiseks*. Vahe *restaureerimisega* on tinglik, kuna arhitektuuriga seotud tööde puhul ei ole võimalik tegeleda pelgalt konserveerimisega. Vana hoone korrastamisel kaasnevad alati uued materjalid kas rekonstruktsioonina või täiesti uue elemendina. Restaureerimise eesmärgiks on uus viimistlus, mille raames eksponeeritakse üksikute fragmentidena näiteid varasemast dekoorist ning tähelepanu keskpunktis on vanale lähedase viimistluse taasloomise tehnoloogilised ja materjalidega seotud aspektid. Sellele vastupidiselt on konserveerimisel seatud teadlikult eesmärgiks vana viimistluse eksponeerimine. Uue viimistlusena lisanduvad vaid vajalikud parandused, mille ulatus sõltub säilinud materjali tehnilisest seisundist ja vanade viimistluspindade vaatlemise kogemusest. Viimane tegur on ajaloolise viimistluse eksponeerimisulatuse kujunemisel määrav, sest tehniliselt stabiilses seisundis viimistluspind võib restaureeriva lähenemisega harjunud silmale tunduda esteetiliselt talumatuna: kulunud, laiguline. Samal ajal on just teatud ulatuses kulumus see omadus, mille abil restaureerimisteooria kirjeldab paatina mõistet, mis olulisima iseloomujoonena kuulub ajaloolise materjali juurde, puudub aga täielikult uusloomingus, kui seda pole tekitatud kunstlikult.

Viimistlustöödele konserveerivalt lähenedes õnnestub meil harvadel juhtudel pealmise viimistluse alt puhastada välja ühte kindlat viimistluskihti. Enamasti on halbade säilimistingimuste tõttu olnud pudenemised pikaajalised, mistõttu puhastamise tulemusena võime kõrvuti näha eri aegadest pärit viimistlusi. Kirikute püsiprobleemideks üldiselt on seinte lagunenud alumised tsoonid ning sademeteveest märgunud võlvikannad, mis tähendab vältimatuid viimistluse parandusi ning tumenenud ja plekilist viimistluspinda, mille eksponeerimine muutmatul kujul on vaatlejale ootamatu. Kuna monokroomsed viimistluspinnad nõuavad konserveerimisel samaväärset tähelepanu kui kõikvõimalikud maalingud, siis eeldab sellise töö ettevõtmine seniste suhtumiste ümberhindamist ja millegi niisuguse väärtustamist, mida ei saa tavamõistes nimetada ilusaks, küll aga autentseks. Vana viimistlus moodustab terviku arhitektuurse vormiga ning on ilus just selle tõttu, vaatamata aja jooksul tekkinud kahjustustele ja kulumisele.

Käsitletav hoone kuulub riiklikult kaitstavate ehitismälestiste hulka, seega tuleb kõikide konserveerimis-, restaureerimis- ja ehitustööde puhul lähtuda Eesti Vabariigi muinsuskaitseseadusest. Tulenevalt antud objekti konserveerimistööde erilisest keerukusest ja kohapealsete otsustuste vajalikkusest peaksid antud töid teostama ajaloolise krohvi konserveerimise kogemusega konservaatorid.

Enne tööde algust taotleb omanik Muinsuskaitseametilt tööde alustamise loa. Pärast tööde algusaja fikseerimist on vaja omaniku-, ehitaja- ja muinsuskaitselise järelevalve teostajate osavõtul kontrollida eritingimustes ja projektis kajastatud väärtuslike detailide olemasolu ja seisukord ning tuvastada nende erinevused ja lahknevused.

2.3.2 Lubimördi retsept

Lubimörtide koostises kasutatavate materjalide valikul peab arvestama konkreetsest olukorrast tulenevate vajadustega, s.t. sokli või seinapinna krohvimiseks kasutatav mört ei pea olema valmistatud terve hooneosa ulatuses ühtse retsepti alusel, vaid järgides valitud mördiretsepti sobivust antud niiskustingimustes (erinevused seina ala- ja ülaosa vahel).

Põhimõtteliselt tuleb kõik mördid valmistada hüdrauliliste omadustega lubja baasil, mitte kasutada tööstuslikult lisanditega rikastatud valmis lubjasegusid. Kindlasti ei tohi kasutatavad mördisegud sisaldada tsementi, v.a. aknaavade aluste vormistamisel, kus on lubatud mördisegule lisada väheses koguses valget tsementi.

2005. a. toimus OÜ Rändmeistri tellimusel Lümandas Priit Penu lubjaahjus (AS Limex) katseline mergelja dolokivi põletamine. Saadud hüdraulilise lubja baasil segatud mördiga tehti sama aasta suvel krohviproovid, mis on osutunud oma struktuurilt väga püsivaks. Seal põletatud lubi sisaldas piisavalt eri suuruses, s.h. ka jämedamaid lubjaosakesi. Tähtis on, et mört sisaldaks keraamilist lisandit — jahvatatud šamott- vm tellispuru. Keraamiline lisand toimib hapniku transportijana, et karboniseerumine toimiks ühtlaselt ka mördikihi sügavamas osas, mitte ainult pindmises kihis.

Retseptid:

Retsept 1 (müüriparandusmört, tühimike ja vuukide täitmine)

MATERJAL	SUHE	SUHE
põletatud mergeljas dolokivi – kuivkustutatud ja sõelutud		1
seguliiv (fr. 0,63–2 mm) lisatud peenikest liiva	~3/5 osa	3
jahvatatud šamott- vm tellisepuru (fr. 0…4 mm)	~2/5 osa	
vesi		

Retsept 2 (pindmised vigastused, pealispinnad, õhem viimistluskiht)

MATERJAL	SUHE	SUHE
põletatud mergeljas dolokivi – kuivkustutatud ja sõelutud		1
seguliiv (fr. 0,0–0,8 mm) lisatud jämedamat liiva	~3/5 osa	2,5
jahvatatud šamotipuru* (fr. 0,3…1,0 mm)	~2/5 osa	
vesi		

* Retseptis 2 ei tohi kasutada tellisepuru, kuna selle tulemusena varieerub liigselt mördi värv

Retsept 3 (konsolideeriv värv)

MATERJAL	SUHE	SUHE
põletatud mergeljas dolokivi – kuivkustutatud ja sõelutud		1
paekivijahu (fr. 0,0–0,3 mm)	~1/3 osa**	1
jahvatatud šamottellisejahu (fr. 0,0…0,3 mm)	~2/3 osa**	
vesi		

** kogus sõltub paekivijahu- ja šamotttellisjahu värvitoonist

Retsept 4 (raidkivide parandus)

MATERJAL	SUHE
põletatud mergeljas dolokivi – kuivkustutatud ja sõelutud (hüdraulilist lubjapastat)	1
kvarts, SiO_2, 0,84% Al 100 µm (Järvakandi Klaasi AS)	1
liiv (fr. 0,0–0,8 mm)	1
lubjakivi (Kaarma dolomiidi) pulbrit	1
vesi	

Retsept 5 (raiddetailide pragude injekteerimine)

MATERJAL	SUHE
põletatud mergeljas dolokivi – kuivkustutatud ja sõelutud (hüdraulilist lubjapastat)	1
Gotlandi lubjakivitolm	3
vesi	

Täpsed mördiretseptid, nendes sisalduva veekoguse, krohvimise ulatuse ja tehnika töötab konserveerimistööde alustades välja konservaator. Toodud retseptides on mahud ja fraktsioonid ligikaudsed.

Viimistluskihi võimalikult ühtlase tulemuse saavutamiseks on soovitav kogu varuda piisavalt suures koguses komponente, et järjest valmistatavate mördi-koguste omadused oleksid ühetaolised. Tähelepanu tuleb pöörata sellele, et lubja segamisel veega aja jooksul hüdrauliline efekt väheneb. Ühtlase lubjakollaka värvitooni saamiseks valmistada korraga võimalikult suur kogus konsolideerivat värvi (retsept 3).

2.3.3 Krohviparanduste tegemise ja konsolideeriva värviga viimistlemise tehnoloogia

— seinapinnal täita suuremad tühimikud ja müüritise vuugid lubimördiga (retsept 1);
— krohviparanduste tegemisel jälgida külgvalguses krohvipinna reljeefi: lisatavad kihid ei tohi moodustada ei kühmu ega lohku;
— krohviparandused uue mördiga (retsept 2) peavad olemasoleva krohviga olema serv serva vastas; mörti ei tohi määrida olemasoleva krohvi peale, kuna seda on hiljem keeruline puhastada; krohviparanduste servad puhastada tööde tegemise käigus;
— enne konsolideerivat värvimist kontrollida seinapinna (mõõdukat) tasasust külgvalgusega, vajadusel tasandada ebatasasused laia pahtlilabida või müürikäiaga;
— valmistada konsolideeriv värvisegu retsept 3 järgi kohapeal. Šamoti- ja kivijahu tuleb enne koguste mõõtmist niisutada, soovitavalt ka lubi. Värv segada mikseriga korralikult läbi;
— niisutada seinapindu veepritsiga. Et krohvi pindmine kiht püsiks konsolideerimise ajal seinapinnal niiskena, tuleb seda korduvalt kasta. Kui krohv on kuiv, imendub värvivesi aluspinda ning värvi ei ole võimalik laiali ajada. Värvimise ajal niisutamine aitab paremini suruda konsolideerivat värvi peentesse pragudesse ja väikestesse aukudesse. Survevesi seob ka lahtise tolmu ning avab tee vigastuse sisse;
— pärast konsolideeriva värvi seinapinnale kandmist tuleb liigne värvimaterjal poorse märja käsnaga kokku korjata. Konsolideeritud pinda pestakse 2-3 korda. Pesemine hoiab värvi märjana ning võimaldab värviosakesi sügavamale vigastatud või pudeda krohvi sisse viia. Konsolideerimise eesmärgiks on värvimaterjali viimine kivi peenematesse pragudesse, sügavamale pudedasse struktuuri, samuti krohvipinna tasandamine ning väiksemate pragude ja vigastuste täitmine, mitte krohvi katmine uue viimistluskihiga. Pinnale jääb õhuke kirme, mis ühtlustab üldvaadet, kuid millest aluspind läbi kumab;
— vajadusel korrata protseduuri.

2.3.4 Konserveerimis- ja restaureerimistööd hooneosade kaupa

2.3.4.1 Eeltööd

Juba eelnevates peatükkides mainitud põhjustel, millest suurimaks teguriks on varemtoimunud linnuseala arheoloogilised kaevetööd, on kiriku põhjakülg jäänud ebasoodsasse niiskusrežiimi. Avatud substruktuurid valgusid pärast väljakaevamist pinnase- ja sadevett täis, mistõttu tuli need katustada. Katusealusesse jääval seinapinnal vohab vetikas. Enne igasuguste müüriparandus- ja viimistlustööde alustamist fassaadidel tuleb seega lahendada linnusevaremete eksponeerimise (või mitte-eksponeerimise) küsimus, soovitavalt maa-alused ruumid liivaga täita ning ajutine varikatus lammutada. Enne nende tööde lõpule viimist ei ole võimalik fassaaditöödega alustada. Esialgu, kuni ümberplaneerimiseni, säilitada 2001. a. projekteeritud vabakujulistest plaatidest käigutee vajalike kalletega ja rennidega. Käigutee puhastada taimestikust.

Käesoleval juhul ei ole võimalik enamikke väärtuslikke detaile hoonest tööde ajaks eemaldada. Enne tööde algust tuleb eelpool loetletud väärtuslikud eksterjööri- ja interjööridetailid tolmu-, krohvi- ja värvipritsmete eest kaitsta kohapeal kinni kattes. Kõige tõhusam on paksema polüetüleenkile kasutamine, kuid sobib ka ehituspapp või jõupaber. Kattematerjali servad kinnitatakse kleeplindiga.

Hoonest kultuuriväärtuslike detailide eemaldamise korral (nt. tornivõlvikus eksponeeritud raidkivid) tuleb need korrektselt inventeerida ja vastavale hoiule üle anda.

Restaureerimis/konserveerimistöödel tuleb järgida kõiki üldisi ehitustööde ohutusnõudeid (vt. p. 2.4).

2.3.4.2 Vundamendid ja sokkel

Olemasolevad vundamendid on pae- ja maakivist lubimördil müüritised. Vundamendid on rahuldavas seisukorras ning nende osas muudatusi ei tehta.

Vastavalt 1990. a. välisviimistluse ja käärkambri tööjooniste projektile oli kiriku sokli perimeeter ette nähtud ~90 cm kõrguselt (maapinna alt) pigitada. Lisaks sellele nähti ette paigaldada piki kiriku perimeetrit sillutisriba järgmiste kihtidega (loetletud ülalt alla): kruus 10…15 cm (laiusega ~60 cm), savi 5 cm (laiusega ~2 m) ja killustik 75 cm.

1989-1991. a. eemaldati kiriku ümbert liigne pinnas ning vundamendi ülemine tsoon (paiguti ka sokkel) võõbati bituumeniga; vähesel määral parandati raidkividest kooriruumi soklisimssi. Ülejäänud ette nähtud tööd jäid teostamata. Seejuures teisaldati pinnas kuni viie meetri kaugusele hoone seinast nii, et kohati tekkis maapinna langus hoone seina poole, mis soodustab antud tsoonis sadevete kogunemist.

Vajalikud tööd:

- eemaldada pinnas terve hoone perimeetri ulatuses, vältida nn valli tekkimist 5…10 m raadiuses ümber kiriku (vt. p. 2.3.4.3)
- sokkel puhastada nõrgasurvelise liivaveega, eelnevalt katsetades leida sobivaim liivafraktsioon, vee temperatuur ja survetugevus
- survepesuga puhastada vundamendi- ja soklikivide paljandunud vuugid mullast ja taimestikust ning lahtisest vuugitäitest, samuti hilisemast bituumenikihist, (tsementmördiga) parandustest ja vetikast; vetikatõrjeks mitte kasutada BORACOLi, kuna see raskendab konserveerivate kihtide pealekandmist soklile
- sokli killunenud müürikivid, samuti vajadusel purunenud sekundaarne materjal (tellised, katusekivitükid jm) asendada algsele dolomiidile sarnast kivi kasutades; kahjustunud piirkonna ulatus selgub kohapeal pärast sokli lahtikaevamist
- soklis olevad tühimikud ja tühjenenud vuugid täita lubimördiga (vt. p. 2.3.2, retsept 1), paigaldatava mördikihi paksus sõltub täidetava koha suurusest. Jämedama mördiga saab täita nii paksult, et ei tekiks mahu kahanemise pragusid
- vuugid ja tühimikud peavad jääma kivipinnaga tasa, suuremad konarused tasandada kihtide lisamisega. Tööriista jälg vuukides kaotada, hõõrudes niiske käsnaga või pühkides tugevama pintsliga
- vana krohv, mis ulatub ümbritsevast müüritisekividest kõrgemale, tuleb säilitada sellisena
- säilitatavate ajalooliste krohvikihtide servad kinnitada, teha krohviparandused lubimördiga (vt. p. 2.3.2, retsept 2, tehnoloogia p. 2.3.3) ning katta konsolideeriva värviga (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- ilma ajaloolise krohvita soklipindadel piirduda konsolideeriva värvimisega (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- dolomiidist sokliliistu konserveerimist/restaureerimist vt. p. 2.3.4.5.

2.3.4.3 Sillutisriba

Vt. joon. AR-8.

Käesoleval hetkel sillutisriba hoone ümber puudub; pinnas koos murukattega ulatub soklimüüritiseni (v.a. osaliselt väljakaevatud linnusealal kiriku põhjaküljel). Kiriku välisseinte niiskusrežiimi parandamiseks ja üleliigse niiskuse eemaldamiseks seintest on vajalik vahetult kirikuseintega külgnevalt pinnaselt juhtida sademeveed vundamendist kaugemale. Osa pinnast on kirikuseinte vahetust lähedusest juba kümmekond aastat tagasi eemaldatud, kuid see on jäetud kirikust 5…8 m kaugusele, moodustades selle ümber madala valli, mis on tekitanud olukorra, et kohati valgub sademevesi hoone suunas. Maa-ala tuleb tervikuna vertikaalplaneerida koos kiviaedade restaureerimise-, piirete ja väravate- ning linnuseala eksponeerimise projektiga.

Pinnasetöödel tagada kiriku lääne- ja lõunaküljel asuvate ristuvate sekundaarsete müüride säilivus.

Vajalikud tööd (kiriku ida-, lääne- ja lõunaküljel):

- tasandada eelnevate pinnaseteisaldamistöödega tekkinud vallid kiriku ümber, vajadusel pinnast kaugemale ära vedades
- maapind sokli kõrval tasandada, tihendada, moodustada kalle hoone seinast eemale (50 cm vahetult hoone seina ääres kaldega 10%, ülejäänud laiuses kaldega 3%)
- maapinnale paigaldada kruusliiv 100 cm laiuselt, paksusega 10 cm, tihendada, säilitada maapinnale antud kalle
- paigaldada kruusaliivakihile nn "bentoniitsavimatid" (Voltex—hüdroisolatsioon-rullmatt, milles naatriumbentoniidi kiht on suletud kahe polüpropüleenist valmistatud geotekstiili vahele), järgides eelnevalt antud kaldeid, seina ääres ülespööre u 10 cm, mattide ülekate min 10 cm
- katta savimatid kasvumullakihiga min 20 cm paksuselt, järgides eelnevalt antud kaldeid
- muld tasandada, külvata muru, rullida (võib paigaldada ka siirdmuru)
- sokliseinte mudaga määrdumise ning kasvupinnase ärauhtumise vastu paigaldada sokli ümber u 50 cm laiune riba, mis koosneb peene (fr. 4–16 mm) ja keskmise (fr. 16–32 mm) fraktsiooniga paekivikillustikust
- paigaldada peaportaali ette kirikusse astumist hõlbustav astmekivi. Aste valmistada lubjakivist, pealispind liivapritsiga karestada, mõõdud võtta vastavalt olukorrale kohapeal
- hooldada muru regulaarselt, vältida pügamisel niiske muru kleepumist soklipinnale

2.3.4.4 Välisseinad, välisviimistlus

Kiriku seinte jaoks on paekivi toodud ümberkaudsetelt Jaagarahu ja Rootsiküla lademete dolomiitpaljanditelt; kivi on murtud Tagavere kihist. Kivi värvitoonid on enamasti kollakad ja pruunikad, harva rohekad. Ka algsed, praeguseks kinnilaotud portaalid on kohalikust kivist. Seevastu hilisemad, eriti kaunite raidtöödega põhja- ja lõunaportaal on Kaarma dolomiidist (vt. p. 2.3.4.5).

Seinapinna lõpetab dolomiidist profileeritud räästakarniis.

Välisseinad on kaetud mitmest perioodist pärit krohvikihtidega, mis üldjoontes kuuluvad säilitamisele. Kahjustused krohvitud pindadel kaardistati 2012. a. Uuringute aruandes on ära toodud ka restaureerimissoovitused.

Ajalooliselt on terve seinapind, v.a. käärkambri sein, olnud krohvitud ja värvitud. Kuna seinapinda ja sellest tulenevalt krohvimist vajavat pinda on väga palju, on ettepanek täiskrohvimise asemel kasutada nn konserveerivat käsitlust: ilma krohvikihtideta jäänud seinakivid konsolideerida, mitte krohvida. Antud lahendus ei ole ajalooliselt õige, kuid annaks võimaluse kaitsta seinte välispinda efektiivsemalt kui kalliks kujunev täiskrohvikate. Täpsemalt vt. konserveerimis-kontseptsiooni p. 2.3.1.

Vajalikud tööd:

- kuna krohvikihid on osadel fassaadidel väga ebastabiilsed, tuleb alustada fassaadide konserveerimist konsolideerivast värvimisest
- vetikakihti ja taimestikku võib proovida seinapinnalt eemaldada nõrga-survelise liivaveega, eelnevalt katsetades leida sobivaim liivafraktsioon, vee temperatuur ja survetugevus; kui krohvikihid on liiga pudedad, otsida muid variante taimestikust vabanemiseks
- killunenud müürikivid, samuti purunenud sekundaarne materjal (tellised, katusekivitükid jm) ja väljakukkunud kividest tekkinud tühimikud asendada vajadusel algsele dolomiidile sarnast kivi kasutades
- tutvuda 2012. a. krohviuuringutel teostatud kahjustuste kaardistustega, mis toob välja erinevat laadi kahjustused: irdumine aluspinnast, pude krohv, krohvi pealispinna kaod ning pealispinna "klaasistumine"; vastavalt kahjustustele määrab konservaator säilitamiseks vajalikud tööd ja täpsustab tehnoloogiad
- tühimikud ja tühjenenud vuugid täita lubimördiga (vt. p. 2.3.2, retsept 1); paigaldatava mördikihi paksus sõltub täidetava koha suurusest. Jämedama mördiga saab täita nii paksult, et ei tekiks mahu kahanemise pragusid
- väiksemad tühimikud täita peenema lubimördiga (vt. p. 2.3.2, retsept 2)
- vuugid ja tühimikud peavad jääma kivipinnaga tasa, suuremad konarused tasandada kihtide lisamisega. Tööriista jälg vuukides kaotada, hõõrudes niiske käsnaga või pühkides tugevama pintsliga
- vana krohv, mis ulatub ümbritsevast müüritisekividest kõrgemale, tuleb säilitada sellisena
- säilitatavate ajalooliste krohvikihtide servad kinnitada, teha krohvi-parandused lubimördiga (vt. p. 2.3.2, retsept 2, tehnoloogia p. 2.3.3) ning värvida konsolideerivalt (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- ilma ajaloolise krohvita seinapindadel piirduda konsolideeriva värvimisega (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- terve seinapind (v.a. raiddetailid) pärast krohviparanduste tegemist värvida konsolideerivalt (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- lõunaseina romaani portaalikilbi ja põhjaseina portaalikilbi ülaosa parandada oma ajaloolise kõrguseni nii, et sellele on võimalik paigaldada väike pliiplekist servakate. Müüritise parandusteks kasutada originaalkivile lähedast dolomiiti.

- lõunaseina romaani portaalikilbi ja põhjaseina portaalikilbi ümarkaarseid portaale ja neid ümbritsevat seinapinda mitte krohvida; seinapinnal kasutada konsolideerivat värvimist (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3), raidkivid jätta katmata (vt. p. 2.3.4.5)
- räästaaluses tsoonis katta silikaattellistest müürilõigud lubimördiga (vt. p. 2.3.2, retsept 2) ühes kihis, järgides ümbritseva ajaloolise krohvikihi faktuuri; mitte taotleda siledat krohviviimistlust
- dolomiidist raiddetailide konserveerimise töökirjeldust vt. p. 2.3.4.5.
- akna- jm avade tellisraamistuse konserveerimise ja kinnimüüritud avade markeerimise töökirjeldust vt. p. 2.3.4.6.

2.3.4.5 Raiddetailid

Kiriku fassaadidel olevad dolomiidist raiddetailid — karniisiplokid, portaalid, akende raidpiidad ja ehisraamistikud, sokliliist, nurgakvaadrid, veesülitid — konserveerida ja eksponeerida.

Kooriruumi akende (A-1, A-2) ehisraamistikud restaureeriti ajavahemikul 1995.-1998. Teiste gooti akende kohta on teostatud 2008. a. kahjustuste kaardistus ja restaureerimise üldised suunised.

Torni- ja pikihoone nurgakvaadrid on erinevas seisukorras, kohati purunenud ja asendatud punase tellisega vm sekundaarse materjaliga, osalt kaetud krohvi- ja värvikihtidega. Lavatooriumi renni ja idaseina veesüliti otsad on murdunud.

Hoones on kaks raidkivist portaali. Peaportaal on kaheastmeline, rohke liigenduse ja raiddekooriga: miniatuurkonsoolid, lehtkapiteelid, nurgalehed ja pärlinöör kaareosas. Portaalinišš on vormistatud keraamiliste tellistega; idapoolses palendis on avaus riivpalgile; müüritise sisepinnas näha hingetappide kinnituspoldid (vt. foto 3.2). Peaportaali kahjustused on pärit ilmselt juba ennesõjaaegsest perioodist: portaalil (vt. foto 3.1) puuduvad mõlemad palenditurbad, idapoolne välisastme mõigas hävinenud, baasid osaliselt hävinenud, läänepoolne kaareplokk asendatud juhusliku materjaliga, terve portaali ulatuses esineb tühjenenud vuuke ja pragusid. Kivipindadel on tugevalt erosioonikadusid, mehaanilisi vigastusi ja soolkahjustusi. Ukse paigaldamisel on portaali rikutud valtsi sisseraiumisega. Tellispalendid kohati varisemisohtlikud. Hingetappide piirkonnas on korrosioonikahjustusi.

Põhjaportaalikilbis on säilinud osa romaaniaegsest portaalist, millega sellesse ehitatud gooti portaal (vt. fotod 3.3, 3.4) moodustab omapärase ansambli. Põhjaportaali iseloomustab eriline ehisraamistik-tümpanon, sammaste leht-kapiteelid, miniatuurkonsoolid. Säilinud on portaaliesine algne lävekivi. Suuremate kahjustuste hulka kuulub terve läänepoolse palendi sisemise astme alusplokk, samal küljel on kapiteel purunenud ja talumiplokk nihkunud. Idapoolne talumiplaat ja nurgaturp osaliselt hävinenud. Nišši tellismüüritises esineb kadusid ja soola-kahjustusi.

Portaalide ja raidkividetailide kohta koostati 2012. a. uuringute aruanne, kus on kaardistatud antud detailide kahjustused ja konserveerimistööde kirjeldus. Ka siin on toonitatud, et raidkiviobjektide konserveerimise eeltingimuseks on stabiilsema sisekliima saavutamine kirikus enne konserveerimistööde algust. Siiski vajavad pikihoone konsoolid kiiret sekkumist lagunemise peatamiseks.

Vajalikud tööd:

- vastavalt kahjustuste ulatusele ja iseloomule ning toetudes 2012. a. koostatud konserveerimise kirjeldustele koostada konservaatoril tegevus-kava, kus täpsustatakse vajaminevad restaureerimise/konserveerimise tehnoloogiad ja kasutatavad materjalid
- portaalidelt jt raidkividelt eemaldada sekundaarsed katte- (lubjavõõp, lubivärv, bituumen) ja varasemad restaureerimiskihid ettevaatlikult mahakraapimise teel, kivi vigastamata
- vajadusel puhtalt tahutud paekivipinnalt lubi eemaldada järgmise seguga (pastaga) tehtud kompressidega (soovituslik koostis): vesi, ammoonium-vesinikkarbonaat (NH_4HCO_3), naatriumvesinikkarbonaat (söögisooda, $NaHCO_3$), triloon B, neutraalne vedel pindaktiivne aine (nõudepesuvahend), karboksüülmetüül tselluloos (tapeediliim). Täpne retsept välja töötada konservaatoril
- portaalidelt eemaldada korrosiooni tekitanud hingetapid
- portaalidelt jt. raidkividelt eemaldada juhuslikud ja ebastabiilsed kivi-parandused ja -asendused
- portaalide (nt peaportaali läänepoolne kaareplokk jm) ja sokliliistu puuduvad osad proteesida vaid konstruktiivse vajaduse korral; väiksemad puuduvad raidkividetailid valmistada mördisegust (retsept 1); põhjaportaali puuduv alusplokk teha kohapealsest vanast sama tooni dolokivimaterjalist
- kahjustustega nurgakvaadrid proteesida vaid konstruktiivse vajaduse korral, varasemad kvaadrite asendused (torni loodenurk) säilitada, puhastada, restaureerida eeltoodud kirjelduse alusel
- idafassaadi veesülitit ja lavatooriumi renni otsa mitte proteesida; konserveerida
- raidkivide restaureerimise tehnoloogia üldkirjeldus:
    a) teha raidkivist detailidele üldine puhastus RS seebi lahusega ja plastharjaga, loputada puhta veega
    b) vajadusel teostada täiendav puhastus nõrga $(NH_4)_2CO_3$ lahuse ja majapidamispaberiga kompressidega
    c) eemaldada samblik, paakunud liiv, tellisepuru, värvi- ja krohvijäägid raidkivipindade pealispinnalt ja uuretest mehaaniliselt pintsli ja skalpelliga

d) soolade eemaldamise jaoks teha kompressid ülimalt nõrga $(NH_4)CO_3$ lahusega savi- ja paberimassi (majapidamispaber) kompress (parim tulemus tuvastada erinevate katsetustega)
e) konsolideerimise vajadusel (peenpraod) töödelda pinda 10% Paraloid B-72 lahusega
f) kiviparandused teha lubimördiga (retsept 4, täpsustada töö käigus)
g) sügavate pragude injekteerimine teha lubimördiga (retsept 5, täpsustada töö käigus)
h) vuugiparandused teha lubimördiga (retsept 2)

- paranduste toon raiddetailidel ühtlustada ümbritseva kivipinnaga; toonimiseks kasutada looduslikke pigmente (ooker, must, umbra) ja akrülaatliimi Plextol 500 3% vesilahust
- raiddetaile konsolideerivalt (retsept 3) mitte katta
- interjööri raiddetaile käsitleda analoogselt, täpse tegevuskava koostab konservaator pärast detailide ülevaatust

2.3.4.6 Välisseinaavad

Kiriku pikihoone-, kooriruumi- ja torni seintes leiduvad avad (s.h. kinnimüüritud-) on joonistel tähistatud vastavalt avatäite tüübile: aknaavad on loendatud vastavalt selles olevale avatäitele A-1 … A-15 ja luugiavad L-1 … L-20. Tähistuste aluseks on võetud muinsuskaitse eritingimustes kasutatud akna- ja ukseavade tähistused.

Lisaks neile leidub seinapinnas rohkesti kinnimüüritud (romaani) avasid ja nende katkeid, mis omaette tähistust ei oma (v.a. säilitatava detaili tähistust).

Avade raamistused on erinevast materjalist. Ainsa tervikliku avaga romaani aken (paekivist sise- ja välispalendid, silluskaared) on säilinud kiriku põhjaseinas ning on kinni müüritud (vt. joon. AR-7). Romaani aknaava on planeeritud eksponeerida nišina, selle lõplikku avamist ei toimu, kuna täitemüüritise sisepinna krohvilt on leitud sirkliga sissekraabitud ringe, mis tulevad säilitada.

Enamik akna- ja luugiavasid on raamistatud punaste tellistega. Aknaaval A-5 on säilinud krohviraamistus, mis on ette nähtud konserveerida. Osa luugiavasid (L-4, L-9…L-17) võivad olla seina suhtes sekundaarsed.

Avatäited vt. p. 2.3.4.7 … 2.3.4.9.

Aknaavade loetelu:

NIMETUS	TÜÜP	MATERJAL Palend/raam	SEISUKORD
A-1	gooti aknaava	tellis/raidraam	restaureeritud (v.a alus)
A-2	gooti aknaava	tellis/raidraam	"

A-3	gooti aknaava	tellis/raidraam	tellisraamistus lagunenud, raidraamistus kahjustatud
A-4	gooti aknaava	tellis/raidraam	"
A-5	gooti aknaava	tellis/raidraam	"
A-6	torni aknaava	tellis/raidraam	"
A-7	torni aknaava	tellis/raidraam	"
A-8	torni aknaava	tellis/raidraam	"
A-9	torni roosaken	paekivi/raidraam	raidraamistus kahjustatud, ava kinni müüritud
A-10	segmentkaarne gooti aken	tellis/raidraam	tellisraamistus lagunenud, raidraamistus kahjustatud
A-11	trepi valgusava	tellisraamistus	hea
A-12	trepi valgusava	tellisraamistus	hea
A-13	käärkambri aknaava	raidkivipiidad	restaureeritud
A-14	vaheseina siseaknaava	dolomiidist seinaava, puitpiirdelauad	hea
A-15	vaheseina siseaknaava	dolomiidist seinaava, puitpiirdelauad	hea

Luugiavade loetelu:

NIMETUS	TÜÜP	MATERJAL	SEISUKORD
L-1	segmentkaarne torniluugiava	tellisraamistus	kinni müüritud, lagunenud
L-2	segmentkaarne torniluugiava	tellisraamistus	lagunenud
L-3	ümarkaarne torniluugiava	tellisraamistus	avariiline (lääneseina pragu)
L-4	segmentkaarne torniluugiava	dolomiidist seinaava	alus lagunenud
L-5	segmentkaarne torniluugiava	tellisraamistus	kinni müüritud, lagunenud
L-6	segmentkaarne torniluugiava	tellisraamistus	kinni müüritud, lagunenud
L-7	ümarkaarne torniluugiava	tellisraamistus	kinni müüritud, avariiline (lääneseina pragu)
L-8	kolmnurkkaarne torniluugiava	tellis- ja raidraamistus	rahuldav
L-9	ümarkaarne torniluugiava	tellisraamistus	rahuldav
L-10	ümarkaarne torniluugiava	tellisraamistus	rahuldav
L-11	ümarkaarne torniluugiava	tellisraamistus	rahuldav

L-12	ümarkaarne torniluugiava	tellisraamistus	alus lagunenud
L-13	ümarkaarne torniluugiava	tellisraamistus	alus lagunenud
L-14	ümarkaarne torniluugiava	tellisraamistus	rahuldav
L-15	ümarkaarne torniluugiava	tellisraamistus	rahuldav
L-16	ümarkaarne torniluugiava	tellisraamistus	rahuldav
L-17	segmentkaarne võlvipealseava	tellisraamistus	alus lagunenud
L-18	ümarkaarne luugiava	tellisraamistus	osaliselt restaureeritud
L-19	kolmnurkkaarne viiluluugiava	tellisraamistus	alus lagunenud
L-20	käärkambri viiluluugiava	puitsillusega dolomiidist seinaava	restaureeritud

Vajalikud tööd:

- enne tööde algust kaardistada avade kahjustused: raidkivid on kihistunud, pealispinnad on murenenud, raidraamide küljest on irdunud tükke, puuduvad terved detailid, kividevahelistest vuukidest on väljapudenenud segu. Tellisraamistustes on kadusid: tellised on kihistunud, murenenud või välja kukkunud, rohkesti on mehaanilisi vigastusi
- vastavalt kahjustuste ulatusele ja iseloomule koostada konservaatoril tegevuskava, kus täpsustatakse vajaminevad restaureerimise/konserveerimise tehnoloogiad ja kasutatavad materjalid
- enne torni luugiavade korrastamist on vajalik olemasolevate torni III korruse luugiavadele toetuvate ebavajalike metallist I-talade demonteerimine
- eemaldada avadest sekundaarsed täitemüüritised: põhjaportaali idakülje juurdeladu, luugiava L-1 täide, luugiavade L-9…L-11 ja L-14…L-16 juhuslikust materjalist alused. Säilitada A-9, L-5, L-6 ja L-7 täitemüüritised, vajadusel kindlustada või uuesti laduda
- tellisraamistused puhastada ettevaatlikult ja minimaalselt neid katvatest krohvi- ja värvikihtidest ilma telliskivi vigastamata
- murenemisohtlikke telliseid võib töödelda looduslikku kivi konsolideeriva vahendiga (nt. Steinfestiger-OH), korrata impregneerimist, kuni konservant on tunginud tervete materjalikihtideni
- avade tellis- ja dolomiitkiviraamistuste juhuslikud ja ebastabiilsed kiviparandused eemaldada. Parandada uute käsitsivalmistatud tellistega peaportaali läänepoolne sisepalend. Avadest eemaldatud vanu telliseid saab vajadusel purustatud kujul kasutada konserveeritavate telliste stabiliseerimiseks tehtavas täidismaterjalis

- ava palendi- ja sillusenurkade tellisraamistuse eksponeerimisel (aknaavad A-2…A-4, torniluugiavad L-1…L3, L-5…L-7) asendada puuduvad tellised originaalile vastava formaadiga käsitsivormitud keraamiliste tellistega; kinnitada mördiseguga (vt. p. 2.3.2, retsept 1). Teiste avaservade tellis- või dolomiidist piirete eksponeerimine otsustatakse tööde käigus, mitte-eksponeerimisel katta krohviga vastavalt seinapinna käsitlusele
- akende ja luukide paigaldamiseks avadesse tuleb tellispiidad restaureerida konstruktiivse vajaduse korral vastavalt ülaltoodud restaureerimisvõtetele. Väiksemate mehaaniliste vigastustega telliseid ei ole vaja parandada ega asendada, kui nad on konstruktiivselt stabiilsed. Kaaluda võimalust paigaldada sama tellis samasse kohta tagasi terve servaga väljapoole (kui see väljaraiumisel ei purune)
- kahjustustega aknaavade raidpiidad proteesida konstruktiivse vajaduse korral; restaureerimise/konserveerimise kirjeldust vt. p. 2.3.4.5
- põhjakülje säilinud silluskaarega romaani aknaavast eemaldada välimine hilisem täitemüüritis, palendi külgedel ja tagaseinas maksimaalselt olemasolevaid krohvikihte säilitades. Avatud sillusel ja palenditel olemasolevad krohvikihid kinnitada, edasist viimistlust vt. p. 2.3.4.4
- roosaknaaval A-9 täidismüüritist ei eemaldata, kuna raidraam võib olla väga ebastabiilses seisukorras. Olemasolev raidkivi konserveerida vastavalt p. 2.3.4.5; täitemüüritis viimistleda vastavalt p. 2.3.4.4, krohvi faktuur eristada ülejäänud seinapinna omast. Puuduvaid raidakna osi ei taastata. Ümmarguse aknaava kontuur interjööris markeerida joonega, täpsustada tööde käigus
- avade alused viia oma algsetele kõrgustele, vajadusel teha selle jaoks täiendavaid uuringuid
- gooti aknaavadesse (A-1…A-8) paigaldada külmakindlast lubjakivist koha järgi välja saetud välimised aknalauad, ühes tükis, paksusega u 60 mm, üleulatus seina välispinnast 40 mm, nurgad ümardatud, pealispind liivapritsiga karestatud. Aknalaua esiserva alla lõigata 15 mm kaugusele 10 mm laiune tilgasoon. Aknalaud kinnitada tüüblite ja mördiseguga (vt. p. 2.3.2, retsept 1 või 2 vastavalt vajadusele)
- gooti aknaavade sisemised aluspinnad vormistada lubimördiga (vt. p. 2.3.2, retsept 2)
- väiksemate avade (müüritrepil, tornis) välimised alused siluda pealt lubitsementmördiga (kasutada ainult valget tsementi, u 10% sideaine mahust) tasaseks, vormistada kalle väljapoole
- välisuste paigaldamist avadesse vt. p. 2.3.4.7; puitluuke vt. p. 2.3.4.8, aknaid vt. p. 2.3.4.9

2.3.4.7 Välisuksed, tuulutusvõred

Kiriku peaportaalis on säilinud üks kahe poolega ilma piidata välisuks VU-1.

Peaukse ukselehtede konstruktsioon: põõnadega püstplangutusele on naelutatud (sepanaelad) servaprofiiliga diagonaallaudis. uks on kinnitatud portaalikividesse kinnitatud hingetappidele latthingedega, millest osasid on lühendatud ja asendatud (vt. fotod 3.1, 3.2). Uks on lukustatav tabakrambiga. Välisuksel on tuvastatav vaid üks õlivärvikiht (ooker).

Ukse laudis on rahuldavas seisukorras ja restaureeritav, värvikiht suures osas maha kulunud, metalldetailid korrodeerunud ning vajavad osaliselt asendamist. Portaali siseküljel on ilmselt varasemast uksest säilinud hingetapid, mida on ette nähtud kasutada ära projekteeritud tuulutusvõre kinnitamiseks. Peaportaalis olev välisuks VU-1 on ette nähtud säilitada ja restaureerida

Põhjaportaalis veel enne II Maailmasõda olnud kalasabamustris laud-voodriga sissepoole avanev üheleheline välisuks on kadunud, avas paikneb ajutine kilp. Põhjaportaali valmistatakse uus puituks VU-2 (vt. joon. AR-9).

Mõlemale sissepääsule on kavandatud puidust tuulutusvõred, tähistatud vastavalt TV-1 ja TV-2 (vt. joon. AR-10, AR-11).

Enamik luugiavasid on praegu kaetud ajutiste kilpidega (puit, osad plekiga kaetud), osalt on kilbid eest ära tõstetud või ära kukkunud.

Välisuste ja tuulutusvõrede loetelu:

NIMETUS	TÜÜP	MATERJAL	MÄRKUSED
VU-1	kahe poolega piitadeta lauduks	puit	restaureerida ol. ol. puituks lisada karplukk, alumine riiv
VU-2	ühe poolega piitadeta lauduks	puit	valmistada uus uks vt. joon. AR-9
TV-1	kahe poolega piitadeta tuulutusvõre	puit	valmistada uus võre vt. joon. AR-11
TV-2	ühe poolega piitadeta tuulutusvõre	puit	valmistada uus võre vt. joon. AR-10

<u>Vajalikud tööd:</u>

- kaardistada kahe poolega puidust välisukse VU-1 kahjustused, fikseerida laudise proteesimise vajadus ja ulatus
- eemaldada ukselehtedelt olemasolevad sepishingelatid, hinnata nende seisukorda ja restaureerida ülemised kaks hingelatti: puhastada vanadest värvikihtidest ning värvida metallivärviga vastavalt värvikaardile
- asendada alumised hingelatid ülemiste hingelattide materjali ja paksuse ning alumiste puitu uuristatud jälgede eeskujul
- puhastada puituksed mehaaniliselt lahtistest värvikihtidest, kasutades infra-punalampi või kuumapuhurit. Värvi eemaldamisel ei tohi kasutada liivapritsi.

- vigastused ja pehastunud lõigud proteesida samaliigilise ja –kvaliteedilise, soovitavalt vana, taaskasutatava kuiva okaspuiduga. Puit peab olema normikohase niiskusastmega (12±2%). Uut puitu enne kasutamist vajaduse korral välitingimustes aeglaselt kuivatada.
- ukselehtede peenemad praod kittida vajadusel puidukitiga.
- ukselehed kruntida, värvida linaseemne õlivärviga mitmes kihis pintsliga vastavalt värvikaardile
- puhastada sepistatud hingetapid lahtistest rooste- ja värvikihtidest, värvida metallivärviga vastavalt värvikaardile
- uksele paigaldada projekteeritud sulused: ukse allosa fikseeriv sepisriiv, karplukk, lukusilt, käepide
- ukseavasse paigaldada ajutine (kuni tornialuse ruumi põrandatöödeni) okaspuidust lävepakk lume sissetuiskamise vältimiseks. Pakk kinnitada ava servades betoonpõrandasse müürinaeltega
- valmistada põhjaportaali uus välisuks VU-2 vastavalt joonisele AR-9. Uks valmistada kvaliteetsest okaspuidust normikohase niiskusastmega (12±2%). Uut puitu enne kasutamist vajaduse korral välitingimustes aeglaselt kuivatada. Välisuks viimistleda analoogselt uksele VU-1. Paigaldada sepis-sulused: hingetapid, (voodrialused) latthinged. Laudise kinnitamiseks kasutada suurepealisi sepisnaelu. Ukse sulgemisviis — riivpalk, kasutades olemasolevaid restaureeritavaid palgipesasid
- Valmistada mõlemasse portaali puidust tuulutusvõred vastavalt joonistele AR-10 ja AR-11. Puidule esitatavad nõuded ja viimistlemine välisustele analoogselt. Tuulutusvõred varustada sepissulustega: hingetapid, hingelatid, tabakrambid.

2.3.4.8 Puitluugid

Enamikel luugiavadel on praegu ees ajutised puitkilbid, osa neist kaetud väljastpoolt plekiga. Kilbid on kinnitatud müüritisse kinnitatud puitlippide või metallpulkade külge seotud traatidega. Osa luugiavasid on lahtised.

Luugiavade kirjeldusi vt. p. 2.3.4.6.

Luukide loetelu:

NIMETUS	TÜÜP	MATERJAL	MÄRKUSED
L-1	linnutõkkevõrk	puit, metall	vt. joon. AR-12
L-2	linnutõkkevõrk	puit, metall	"
L-3	linnutõkkevõrk	puit, metall	"
L-4	linnutõkkevõrk	puit, metall	"
L-5			täitemüüritist ei eemaldata, luuki ei paigaldata

L-6			täitemüüritis restaureerida, luuki ei paigaldata
L-7			täitemüüritis restaureerida, luuki ei paigaldata
L-8	riivpalgiga luuk	puit	vt. joon. AR-13
L-9	piitadega luugid	puit	vt. joon. AR-14
L-10	piitadega luugid	puit	"
L-11	piitadega luugid	puit	"
L-12	piitadega luugid	puit	"
L-13	piitadega luugid	puit	"
L-14	piitadega luugid	puit	"
L-15	piitadega luugid	puit	"
L-16	piitadega luugid	puit	"
L-17	piitadega luugid	puit	"
L-18	piitadega luugid	puit	"
L-19	piitadega luugid	puit	"
L-20			olemasolev luuk restaureerida

Vajalikud tööd:

- eemaldada luugiavadest amortiseerunud avatäited, restaureerida/konserveerida avad vastavalt p. 2.3.4.6
- valmistada uued piitadega puitluugid vastavalt joonistele AR-13 ja AR-14. Luugid valmistada kvaliteetsest okaspuidust normikohase niiskusastmega (12±2%). Uut puitu enne kasutamist vajaduse korral välitingimustes aeglaselt kuivatada.
- Luugid kruntida, värvida linaseemne õlivärviga mitmes kihis pintsliga vastavalt värvikaardile Paigaldada sepissulused: hingetapid, latthinged, sepishaagid (vt. joon. AR-15…AR-18). Luugi L-8 sulgemisviis — riivpalk olemasolevatesse remonditavatesse pesadesse
- Valmistada puitraamis mitteavatavad linnutõkkevõrgud vastavalt joonisele AR-12, kinnitada müüri külge löökankrutega. Viimistleda metallivärviga vastavalt värvikaardile

2.3.4.9 Aknad

Kirikus on kaks restaureeritud raidraamistusega ja vitraažraamidega kooriruumi akent (A-1, A-2). Teistesse gooti aknaavadesse on avatäited projekteeritud 2008. a. (arh. I. Kannelmäe, vt. p. 1.2.2). Avadesse A-3…A-5 on olemasolevatesse raidkivi- ja tellispiitadesse ette nähtud vitraažaknad, avadesse A-6…A-8 veidi lihtsamad puit-raamis aknad. Aknaavasse A-10 projekteeriti turvaklaasiga aken.

Käesolevas projektis ei ole neid aknaid ümber kavandatud.

Avades A-3…A-10 asuvad ajutised plekiga kaetud puitkilbid. Avade A-11 ja A-12 ette on paigaldatud ajutised PVC-võrguga linnutõkkevõrgud. Aken A-13 restaureeriti vitraažaknana koos käärkambri restaureerimistöödega. Aknad A-14 ja A-15 on kuue klaasiruuduga historitsistlikus puitraamis olevad kiriku sisemise vaheseina siseaknad (endisele oreliväärile). Viimased on heas seisukorras.

Akende loetelu:

NIMETUS	TÜÜP	MATERJAL	MÄRKUSED
A-1	kooriruumi gooti aken		olemasolev restaureeritud raidpiitades vitraažaken
A-2	kooriruumi gooti aken		"
A-3	gooti aken	vitraažaken	lahendatud 2008. a. projektiga, joon. 1
A-4	gooti aken	vitraažaken	lahendatud 2008. a. projektiga, joon. 2
A-5	gooti aken	vitraažaken	lahendatud 2008. a. projektiga, joon. 3
A-6	torni gooti aken	puit, klaas	lahendatud 2008. a. projektiga, joon. 4
A-7	torni gooti aken	puit, klaas	lahendatud 2008. a. projektiga, joon. 5
A-8	torni gooti aken	puit, klaas	lahendatud 2008. a. projektiga, joon. 6
A-9			endine roosaknaava, täitemüüritis säilitada
A-10	segmentkaarne aken	puit, turvaklaas	lahendatud 2008. a. projektiga, joon. 7
A-11	müüritrepi valgusava	puit, metallvõrk	vt. joon. AR-12
A-12	müüritrepi valgusava	puit, metallvõrk	vt. joon. AR-12
A-13			olemasolev restaureeritud raidpiitades vitraažaken
A-14	vaheseina 6-ruuduga aken	puit, klaas	restaureerida olemasolevad aknad
A-15	vaheseina 6-ruuduga aken	puit, klaas	restaureerida olemasolevad aknad

<u>Vajalikud tööd:</u>

- eemaldada aknaavadest amortiseerunud ajutised kilbid, restaureerida/ konserveerida avad avad vastavalt p. 2.3.4.6
- valmistada uued avatäited 2008. a. projekti seletuskirja ja jooniste kohaselt
- väikesed müüritrepi valgusavad katta uute linnutõkkevõrkudega, mis

kinnitada müürinaeltega

- aknad A-14 ja A-15 restaureerida. Aknaraamid tõsta piitadest välja, restaureerida eraldi. Aknapiidad restaureerida kohapeal. Piidad puhastada lahtistest värvikihtidest ja tolmust, peenemad praod kittida vajadusel puidukitiga. Piidad värvida linaseemne õlivärviga vastavalt värvikaardile. Siseseinte krohvi- ja värvimistööde ajaks katta piidad kinni
- aknaraamide originaalklaasid säilitada. Puitosad puhastada olemasolevatest lahtistest värvikihtidest. Kahjustunud puitu vajadusel proteesida sama-tüübilise vana puiduga. Peenemad praod kittida puidukitiga. Paigaldada olemasolevad klaasid, kittida. Aknaraamid puhastada tolmust, värvida linaseemne õlivärviga vastavalt värvikaardile
- akende puidust piirdelauad restaureerida analoogselt. Paigaldada pärast siseseinte viimistlemist

2.3.4.10 Katus

Kiriku pikihoonele projekteeriti 2012. a. ning paigaldati järgneval aastal uus puitsarikatel kivikatus munk-nunn-tüüpi punakaspruuni savikiviga. Seoses sellega parandati ja restaureeriti pikihoone karniise ning paigaldati räästa tuulutuspilusse peenesilmaline linnutõkkevõrk. Rajati pööningule puidust käigutee.

Käesoleva projektiga säilitatakse olemasolev torni kelpkatus; võimaluse avanedes tuleb taastada tornikiiver oma esialgses mahus (vt. joon. AR-5…AR-7, märgitud punktiiriga), võttes aluseks 1960. a. lahenduse (arh. K. Aluve, ins. V. Buldas).

Torni uus plekk-katus on pikihoonega visuaalse ühtsuse saavutamiseks planeeritud värvida oranžikaspruuni metallivärviga.

<u>Vajalikud tööd:</u>

- eemaldada torni katuselt amortiseerunud terasplekk. Kui puit-konstruktsiooni ja plekikahjustused ei ole suured ning valtsid on veetihedad, võib olemasolevat katusekatet remontida ning uuesti värvida
- kontrollida plekialuse laudroovitise ja kandekonstruktsioonide seisukorda. Vajadusel pehastunud puitosad proteesida samatüübilise saematerjaliga, laudis remontida
- torni katus katta vajadusel uue tsingitud terasplekist katusekattega, kasutades kahekordseid tihendatud valtse. Vormistada uus katuseluuk olemasolevasse kohta
- torni plekk-katus kruntida ja värvida kahe aasta möödudes katusevärviga vastavalt värvikaardile
- projekteerida piksekaitsesüsteem, torni ja pikihoone katustele paigaldada piksekaitsevardad

2.3.4.11 Siseviimistlus, maalingud

Seinte ja võlvide sisepinnad on analoogselt välispindadele kaetud mitmest perioodist pärit krohvikihtidega, mis kõik üldjoontes kuuluvad säilitamisele. Läbi ajaloo on kirik olnud alati ka seest värvitud hallikas- või kollakasvalge lubivärviga.

Seoses kirikus pikka aega olnud niiskusprobleemidega on sisepindadel ulatuslikud niiskuskahjustused, mis on viinud massiivsele vetikate vohamisele ning krohvipindade irdumisele. Kahjustused ja nende põhjused krohvitud pindadel, samuti maalinguleiud kaardistati 2012. a. Täpsemalt vt. p. 2.2.6.4.

Eelpool mainitud uuringute aruandes on ära toodud ka restaureerimis-soovitused, mis hiljuti restaureeritud kooriruumi krohvi- ja maalingukihtide seisundit silmas pidades paigutab interjööri restaureerimise terves kirikus tehtavate ehitustööde pingereas viimaste hulka.

Kooriruumis 1990-ndatel aastatel teostatud konserveerimistööd (eelkõige altari baldahiini kujutav maaling) vajavad uut kontseptsiooni, kuna tolleaegne tulemus on liigniiskuse tõttu osaliselt hävinud. Pikihoone võlvikutele maalitud kilpkaari ja roidekive ei saa kohati avada, kuna pind on "klaasistunud". Konserveerivale lähenemisele vastavalt tuleb loobuda maalingute rekonstruktsioonidest. Maalingute avamist ja konserveerimist puudutav tööde kava koostatakse konservaatori poolt.

<u>Vajalikud tööd:</u>

- tutvuda 2012. a. krohviuuringutel teostatud kahjustuste kaardistustega, mis toob välja erinevat laadi kahjustused: irdumine aluspinnast, pude krohv, krohvi pealispinna kaod ning pealispinna "klaasistumine"; vastavalt kahjustustele määrab konservaator säilitamiseks vajalikud tööd ja tehnoloogiad, arvestades krohvil olevaid maalingukihte
- säilitatavate ajalooliste krohvikihtide servad kinnitada, teha krohvi-parandused lubimördiga (vt. p. 2.3.2, retsept 2)
- vajadusel kinnitada krohvikihid konsolideeriva värviseguga (vt. p. 2.3.2, retsept 3, p. 2.3.3)
- seinte- ja võlvide sisepinnad puhastada vetikast ja klaasistunud pinnaga krohvikihtidest nõrgasurvelise liivaveega, eelnevalt katsetades leida sobivaim liivafraktsioon, vee temperatuur ja survetugevus; pärast kuivamist puhastada tühimikud üleliigsest liivast surveõhuga
- killunenud müürikivid, samuti purunenud sekundaarne materjal (tellised, katusekivitükid jm) ja väljakukkunud kividest tekkinud tühimikud konstruktiivsel vajadusel asendada algsele dolomiidile sarnast kivi kasutades
- interjööris tuleb asendada kahjustunud tellised vaid konstruktiivse vajaduse korral; dekoratiivsena eksponeeritud telliseid ei tule asendada.
- tühimikud ja tühjenenud vuugid täita lubimördiga (vt. p. 2.3.2, retsept 1); paigaldatava mördikihi paksus sõltub täidetava koha suurusest. Jämedama

mördiga saab täita nii paksult, et ei tekiks mahu kahanemise pragusid
- väiksemad tühimikud täita peenema lubimördiga (vt. p. 2.3.2, retsept 2)
- vuugid ja tühimikud peavad jääma kivipinnaga tasa, suuremad konarused tasandada kihtide lisamisega. Tööriista jälg vuukides kaotada, hõõrudes niiske käsnaga või pühkides tugevama pintsliga
- vana krohv, mis ulatub ümbritsevast müüritisekividest kõrgemale, tuleb säilitada sellisena
- säilitatavate ajalooliste krohvikihtide servad kinnitada, teha krohviparandused lubimördiga (vt. p. 2.3.2, retsept 2, tehnoloogia p. 2.3.3) ning värvida konsolideerivalt (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- ilma ajaloolise krohvita seinapindadel piirduda konsolideeriva värvimisega (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- terve seinapind (v.a. raiddetailid) pärast krohviparanduste tegemist värvida konsolideerivalt (vt. p. 2.3.2, retsept 3, tehnoloogia p. 2.3.3)
- dolomiidist raiddetailide konserveerimise töökirjeldust vt. p. 2.3.4.5.
- maalingute konserveerimise konkreetsed meetmed koostab konservaator pärast maalingukihtide täiendavaid uuringuid.

2.3.4.12 Põrand

Kiriku pikihoones ja tornialuses ruumis 2/3 ulatuses on erinevatest ajaperioodidest pärit betoonpõrandad, mille all võivad olla varasemad põrandakihid; ülejäänud 1/3 põrandapinnast katab pinnas (liiv, muld).

Kooriruumi põrand, mis on pikihoone omast u 24 cm kõrgem (2 trepiastet võidukaare all) restaureeriti 1997. a. ning see koosneb vabakujulistest dolomiitplaatidest ja hauaplaatidest; põranda edelaosas on klaasiga kaetud ekspositsioonikamber. Põrand on ette nähtud sellisena säilitada.

Vastavalt muinsuskaitse eritingimustele säilitatakse pikihoones ja tornialuses ruumis betoonpõrand praeguses mahus kuni täiendavate uuringuteni.

Torni puitpõrandad ja puittrepp remonditakse.

<u>Vajalikud tööd:</u>
- puhastada pikihoone betoonpõrand prahist ja liivast. Kaardistada põranda olemasolev seisukord edasiste tööde tegemiseks
- määrata uuringutega algse põranda tasapind (lähtekohaks mõõdetud N-portaali lävekivi). Vastavalt sellele koostada projekt kiriku põrandate taastamiseks
- tasandada uuringutest jäänud pinnase ebatasasused pikihoones. Pinnas katta ajutiselt peene kuni keskmise fraktsiooniga paekivikillustikuga
- kuni uuringuteni ja uue dolomiitplaatidest põranda ehitamiseni tasandada olemasolevad ebatasasused betoonpõrandal ning tähistada markeeriva kleeplindiga külastajate ohutuse tagamiseks erinevad tasapinnad

2.3.4.13 Siseuksed

Seoses altariruumi ja käärkambri restaureerimisega paigaldati uued tammepuidust püstlaudadest siseuksed U-1 ja U-2. Uksed on heas seisukorras ja ei vaja restaureerimist.

Vastavalt tuleohutuse osas (vt. p. 2.2.3) ära toodud nõuetele on kirik jaotatud kolmeks sektsiooniks, mis tingib tuletõkkeseintesse vastava tulepüsivusastmega tuletõkkeuste paigaldamist. Uksed paigaldatakse olemasolevatesse tellisraamistusega kolmnurkse sillusega avadesse (vt. joon. AR-1, AR-2).

Siseuste loetelu:

NIMETUS	TÜÜP	MATERJAL	MÄRKUSED
U-1	ühe poolega uks	tammepuit	olemasolev
U-2	ühe poolega uks	tammepuit	"
U-3	ühe poolega tuletõkkeuks EI30	puit	valmistada uus tuletõkkeuks vt. joon. AR-15
U-4	ühe poolega tuletõkkeuks EI30	puit	valmistada uus tuletõkkeuks vt. joon. AR-15

<u>Vajalikud tööd:</u>

- remontida olemasolevad tellisukseavad ustele U-3 ja U-4 vastavalt p. 2.3.4.6 toodud konserveerimisvõtetele
- valmistada uued okaspuidust tuletõkkeuksed vastavalt joonisele AR-15
- uksed valmistada kvaliteetsest normikohase niiskusastmega (10±2%) okaspuidust. Uut puitu enne kasutamist vajaduse korral välitingimustes aeglaselt kuivatada
- ukselehed kruntida, värvida linaseemne õlivärviga mitmes kihis pintsliga vastavalt värvikaardile
- paigaldada tuletõkketihendid ja sulused (vt. joon. AR-16…AR-18)
- uksed U-3 ja U-4 peavad valmiskujul ja paigaldatuna vastama tuletõkkeuste EI30 nõuetele

2.3.5 Värvilahendus

Värvitoonide numbrid fassaadide joonistel (vt. joon. AR-5, AR-6, AR-7).
Värvitoonid on valitud kataloogidest *Teknos RAL värvitoonide kataloog* (1, 4) ja *Majatohtri linaõlivärvide toonikaart* (3). Seinapinna ja karniisi värvitoon (2) on retseptiga 3 kokkusegatud konsolideeriva värvi naturaalne vanavalge toon (sõltuvalt šamott- ja paekivijahu sisaldusest).

①	torni katus, käärkambri katus	RAL 8003
②	karniis, seinapind	lubjavalge
③	puitluugid, tuulutusvõred, välisuksed	4010-G50Y
④	võred, avatäidete metallosad, tõmbankrud	RAL 7021

2.4 Konserveerimis/restaureerimistööde organiseerimine

2.4.1 Ehituskorraldus

Enne konserveermis/restaureerimistööde algust koostab töövõtja objekti sisekorra eeskirjad, keskkonnaohutuse plaani, jäätmekava ja kooskõlastab selle kohaliku omavalitsuse vastava inspektoriga.

Kõik ehitusplatsil töötavad inimesed peavad olema instrueeritud ohutustehnika nõuete suhtes. Ohutuse ja töötervishoiu eest ehitusplatsil vastutab täielikult ehitustööde töövõtja vastavalt Vabariigi Valitsuse 8. detsembri 1999. a määrusele nr 377 "Töötervishoiu ja tööohutuse nõuded ehituses".

Muinsuskaitsealuselise ehitismälestise staatust silmas pidades järgida nõudeid, mis on ära toodud punktides 1.4.4 ja 2.3.1.

Ehitusplatsil tuleb erilist tähelepanu pöörata järgmistele ohutusnõuetele:

- Ohtlike tsoonide piirid tähistada hästi nähtavate märkidega;
- Pimedal ajal ohtlikud- ja töötsoonid valgustada;
- Töötamise ajal on töötsoonis ja ohtlikus tsoonis on kõrvaliste inimeste viibimine keelatud;

- Kõik ehitusplatsil töötavad ja viibivad inimesed peavad vajadusel kandma kaitsekiivreid;
- Kõrvaliste isikute juurdepääs ehitusplatsile ja töötsoonidesse peab olema tõkestatud piiretega;
- Augud maapinnal ja põrandates peavad olema kaetud;
- Trepid, töölavad ja lahtised platvormid peavad olema piiratud;
- Maandatud peavad olema kõik elektriseadmed. Töötamise vaheaegadel vool välja lülitada;
- Ehitusplatsile peab olema juurdesõidu võimalus tuletõrjemasinatele;
- Ehitusplatsil peavad olema nähtaval kohal tuletõrjevahendid.

2.4.2 Jäätmekäitlus

Enne konserveermis/restaureerimistööde algust koostab töövõtja jäätme-kava ja kooskõlastab selle kohaliku omavalitsuse vastava inspektoriga. Jäätmekava peab olema vastavuses Orissaare vallavolikogu 16. detsembri 2010. a. määrusega nr. 43 "Muhu ja ida-Saaremaa valdade ühine jäätmehoolduseeskiri".

Ehitusjäätmete käitlemise eest vastavalt kehtivate eeskirjade nõuetele vastutab jäätmevaldaja, s.o. jäätmetekitaja, kelle valduses on jäätmed.

Ohtlikud ja mitteohtlikud jäätmed sorteeritakse ja kogutakse eraldi konteinerisse. Ohtlikud jäätmed antakse vastavalt kehtestatud korrale üle ohtlike jäätmete käitlemise litsentsi omavale ettevõttele. Mitteohtlikud jäätmed, mida on võimalik taaskasutada, kasutatakse samal või teistel objektidel või antakse üle jäätmekäitlemislitsentsi omavale ettevõttele kes ladustab need püsijäätmete prügilasse.

Lähim jäätmejaam asub Maasis, Orissaare vallas (Maasi Jäätmehoolduse OÜ).

Ehitus- ja lammutustöödel saab jäätmeid vältida ja vähendada mõistliku töökorraldusega jäätmete tekkekohas. Kindlasti tuleb ehitus- ja lammutusjäätmed sorteerida tekkekohas liikidesse, et võimaldada nende laiaulatuslikku korduv- ja taaskasutamist. Eraldi tuleb sorteerida puit, paber ja papp, metall, mineraalsed jäätmed (kivid, tellised, krohv, betoon, klaas jne).

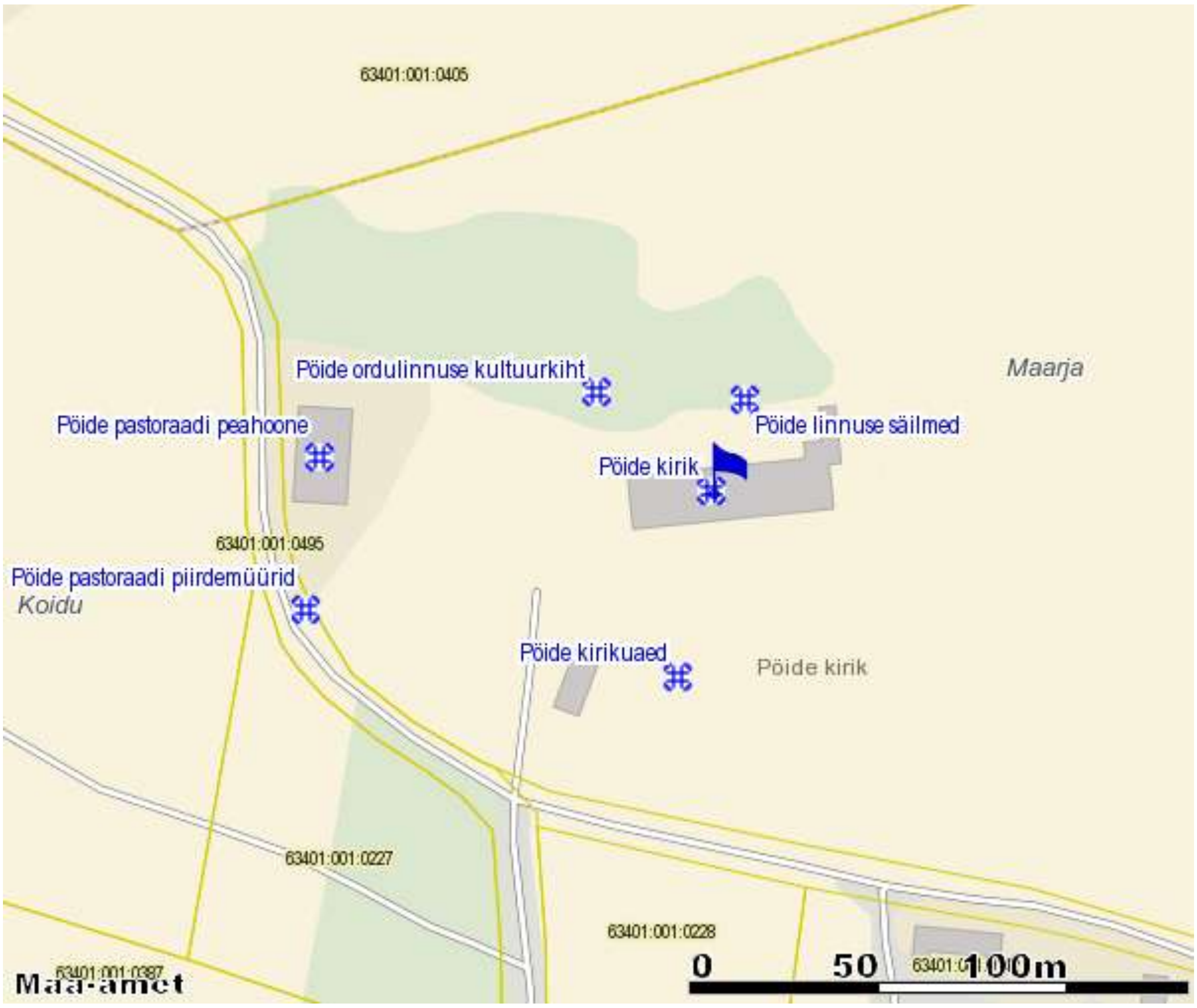
Mahukad ehitusjäätmed, mida oma kaalu või mahu tõttu pole võimalik paigutada konteinerisse ja mida ei anta kohe üle jäätmekäitlusettevõttele, paigutatakse krundi piires selleks eraldatud territooriumile nende hilisemaks transportimiseks jäätmekäitluskohta.

Seletuskirja koostas: arhitekt Elo Sova
01.09.2013

B GRAAFILINE OSA

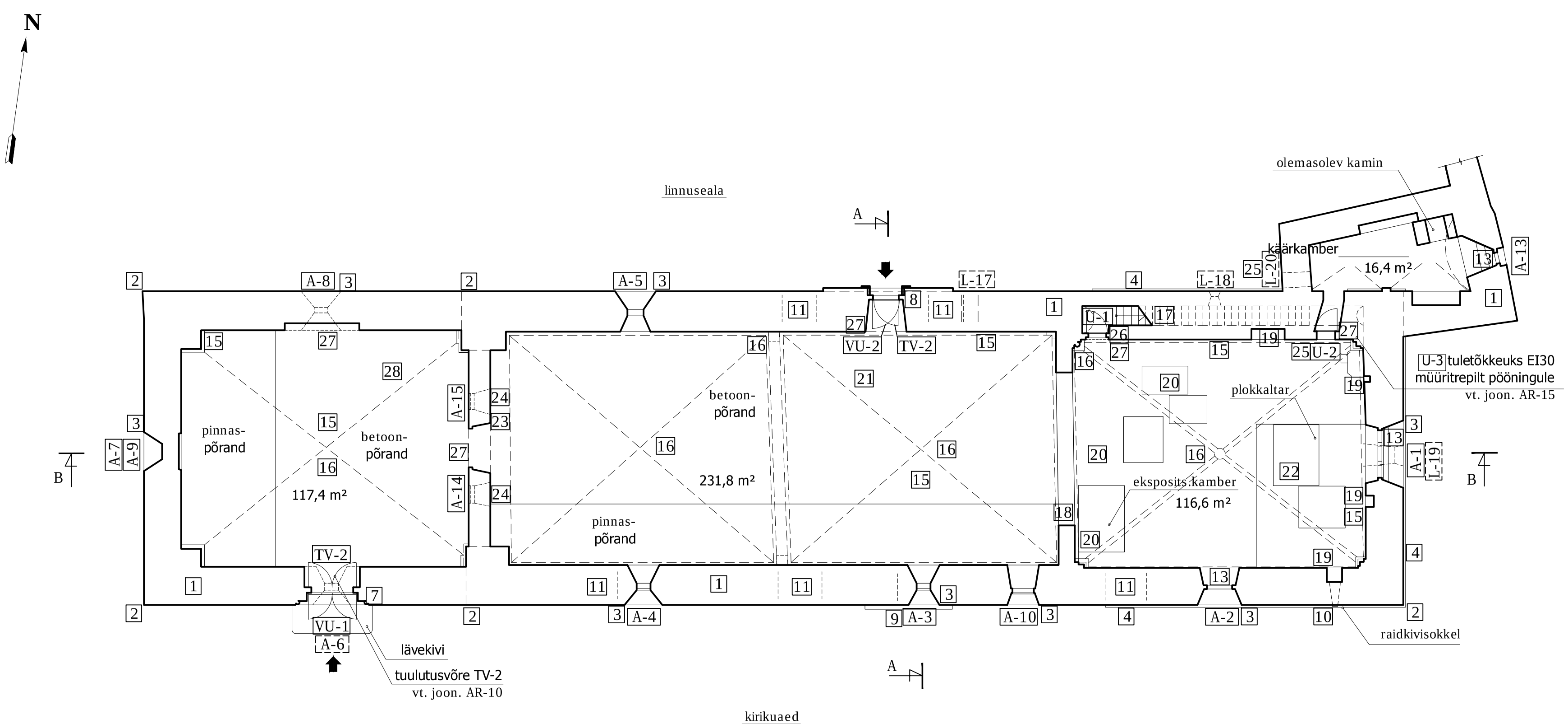
1 JOONISED

SITUATSIOONISKEEM



 PÕIDE KIRIK
reg. nr. 21058

PÕHIPLAAN M 1:200



TÄHISTUSED:

- olemasolevad konstruktsioonid
- ülevalpool plaani pinda asuvad konstruktsioonid
- varjatud konstruktsioonid
- 1 säilitatavad detailid
- A-1 avad, avatäited
- ⬅ sissepääs hoonesse

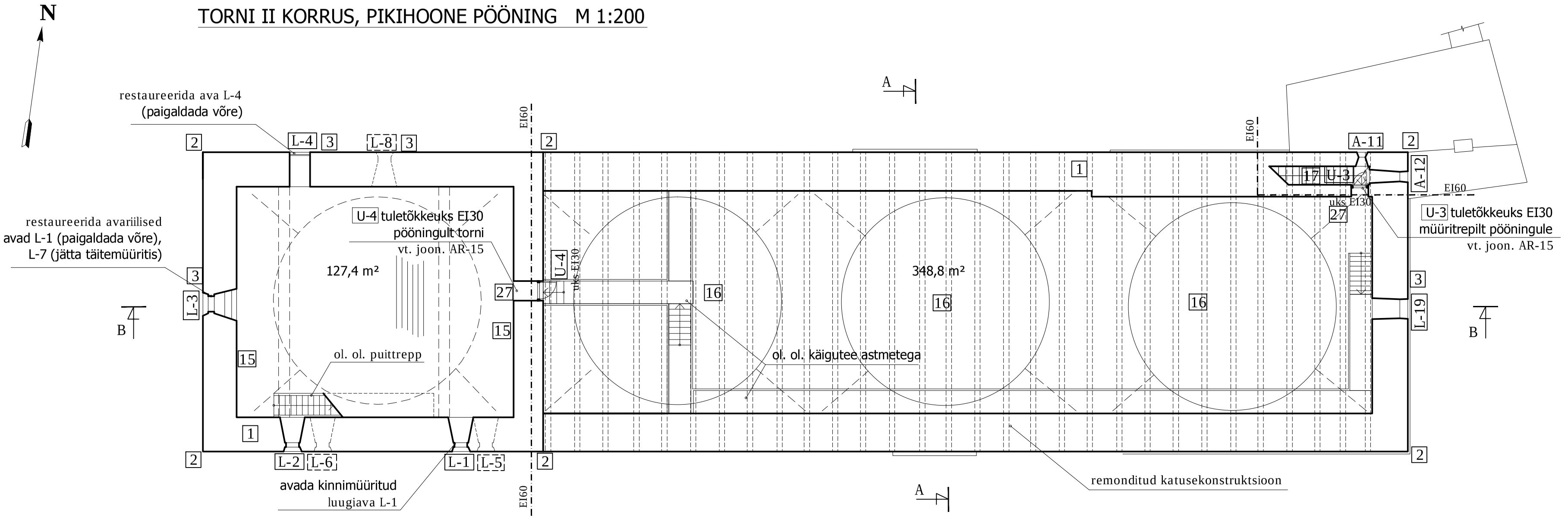
MÄRKUSED:

1. Joonise aluseks on 1942. a. ülesmõõtmisjoonis (J. Armalik).
2. Joonist lugeda koos seletuskirjaga.
3. Plaanil on kujutatud korraga kõiki pikihoone eri kõrgusel paiknevaid akna- ja luugi-avasid. Nende paiknemist vt. joon. AR-3 ... AR-7.
4. Lõiget A-A vt. joon. AR-3, lõiget B-B vt. joon. AR-4.

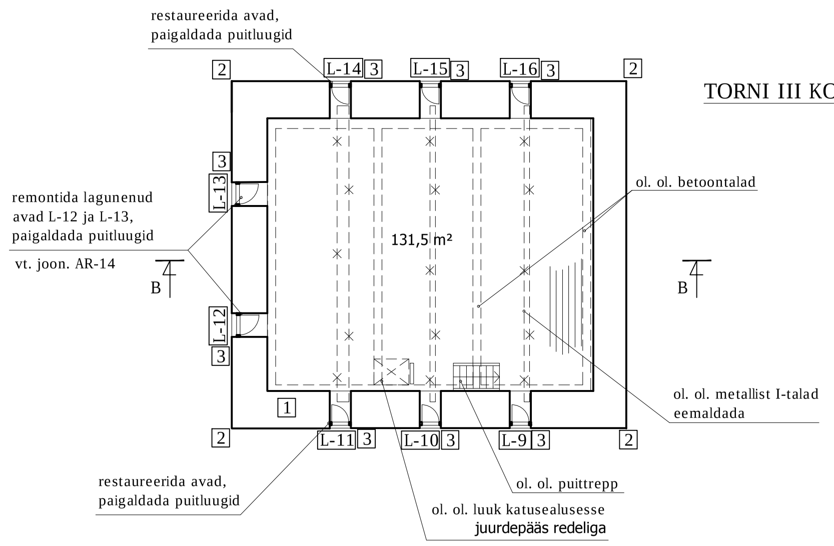
TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				PÕHIPLAAN	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-1	MÕÕTKAVA 1:200
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399					

TORNI KORRUSTE PLAANID M 1:200

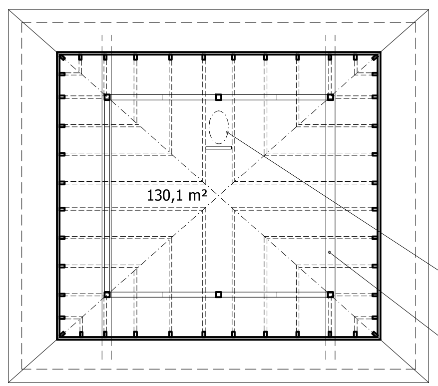
TORNI II KORRUS, PIKIHOONE PÖÖNING M 1:200



TORNI III KORRUS M 1:200



TORNI PÖÖNING M 1:200



MÄRKUSED:

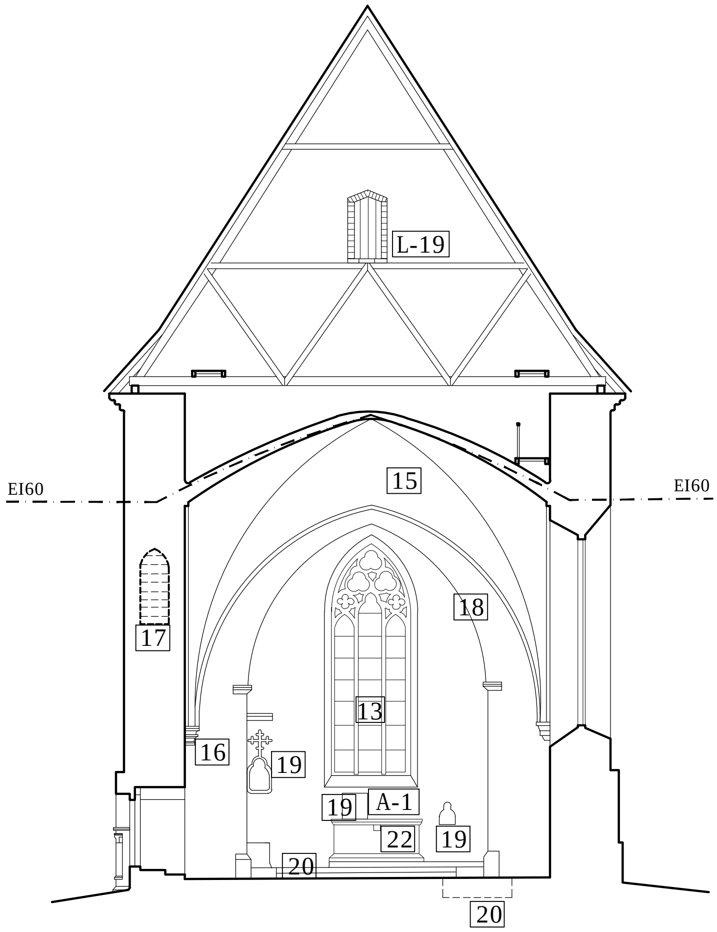
1. Joonise aluseks on 1942. a. ülesmõõtmisjoonis (J. Armalik).
2. Joonist lugeda koos seletuskirjaga.
3. Lõiget A-A vt. joon. AR-3, lõiget B-B vt. joon. AR-4.

TÄHISTUSED:

- 1 — säilitatavad detailid
- L-1 — avad, avatäited
- EI60 — tuletõkkesektsiooni piir

TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				TORNI KORRUSTE PLAANID	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-2	MÕÕTKAVA 1:200
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399					

LÕIGE A-A M 1:200



TÄHISTUSED:

1 säilitatavad detailid

A-1 avad, avatäited

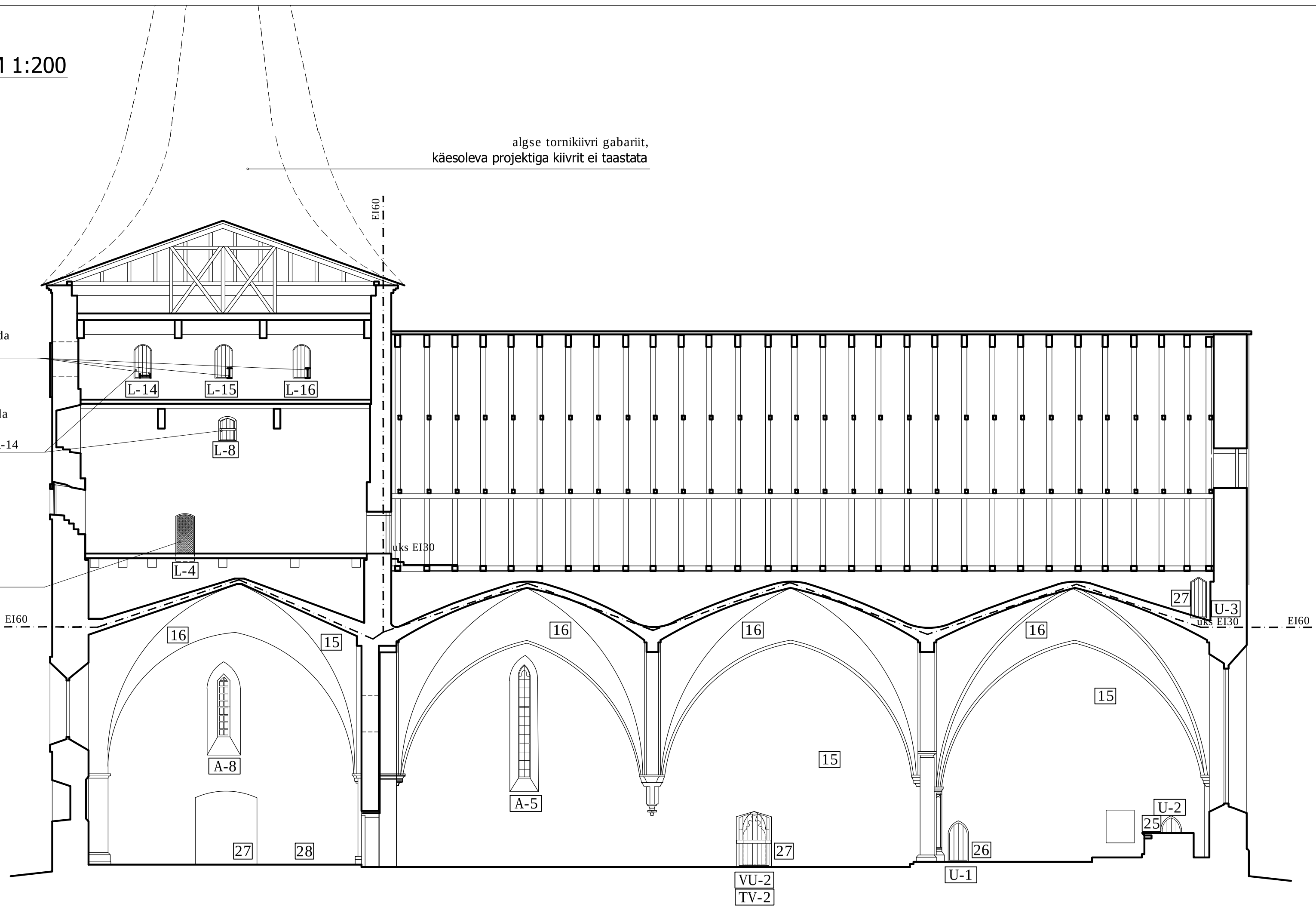
MÄRKUSED:

1. Joonise aluseks on 1942. a. ülesmõõtmisjoonis (J. Armalik).
2. Joonist lugeda koos seletuskirjaga.
3. Hoone kõrgusmärgid on olemasolevad.

TÖÖ PÕIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS LÕIGE A-A	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-3	MÕÕTKAVA 1:200

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

LÕIGE B-B M 1:200



TÄHISTUSED:

- olemasolevad konstruktsioonid
- ülevalpool plaani pinda asuvad konstruktsioonid
- varjatud konstruktsioonid
- 1 — säilitatavad detailid
- A-1 — avad, avatäited
- EI60 — tuletõkkesektsiooni piir

MÄRKUSED:

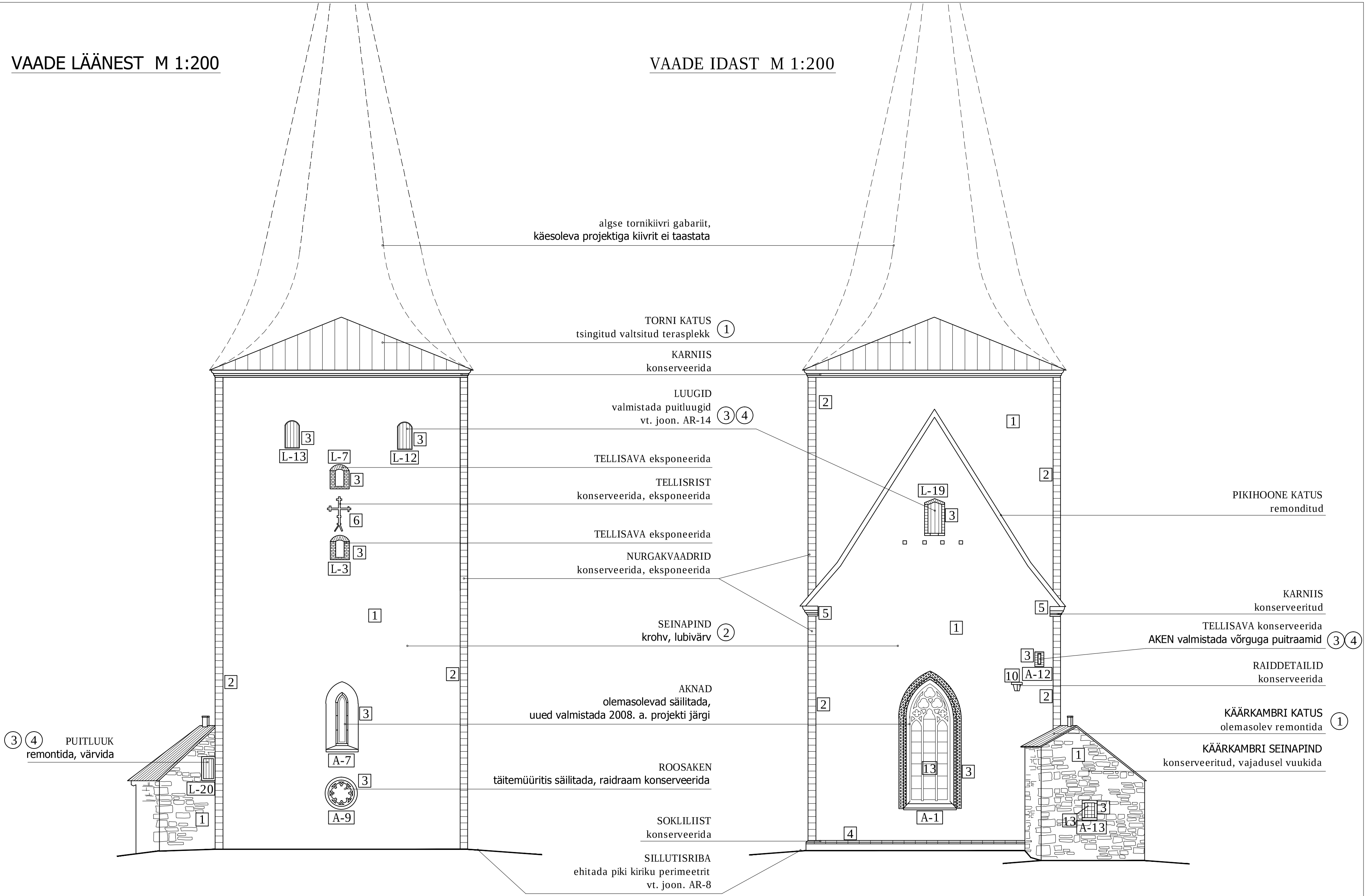
1. Joonise aluseks on 1942. a. ülesmõõtmisjoonis (J. Armalik).
2. Joonist lugeda koos seletuskirjaga.
3. Hoone kõrgusmärgid on olemasolevad.

TÖÖ: PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS: LÕIGE B-B	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-4	MÕÕTKAVA 1:200

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

VAADE LÄÄNEST M 1:200

VAADE IDAST M 1:200



MÄRKUSED:

1. Joonise aluseks on ülesmõõtmisjoonised.
2. Joonist lugeda koos seletuskirjaga.

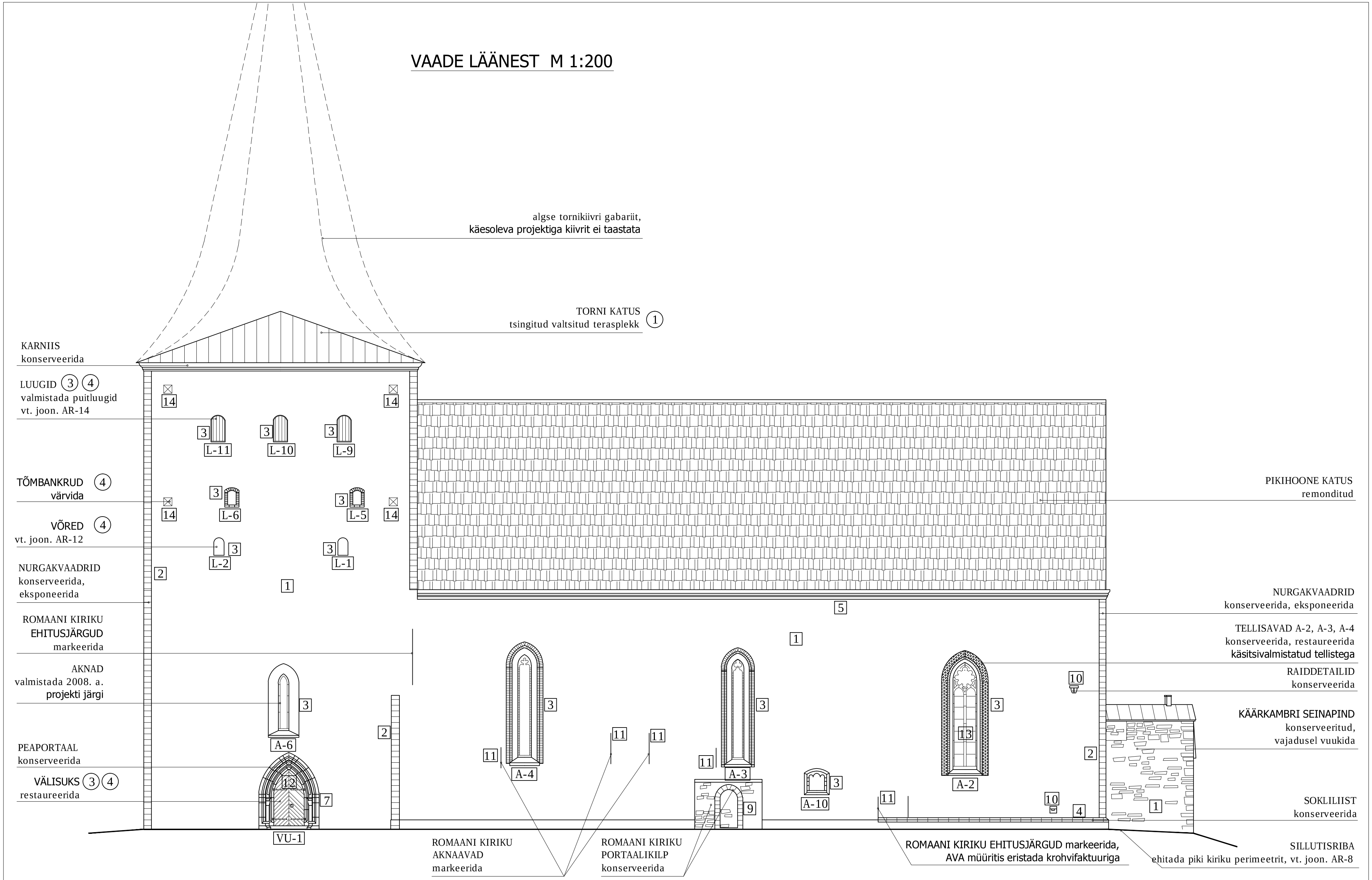
TÄHISTUSED:

- [1] säilitatavad detailid
- [A-1] avad, avatäited
- (1) värvitoon

TÖÖ: PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS: VAADE LÄÄNEST, VAADE IDAST
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20 / STAADIUM PÕHIPROJEKT
				JOONIS AR-5 / MÕÕTKAVA 1:200

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

VAADE LÄÄNEST M 1:200



MÄRKUSED:

1. Joonise aluseks on ülesmõõtmisjoonised.
2. Joonist lugeda koos seletuskirjaga.

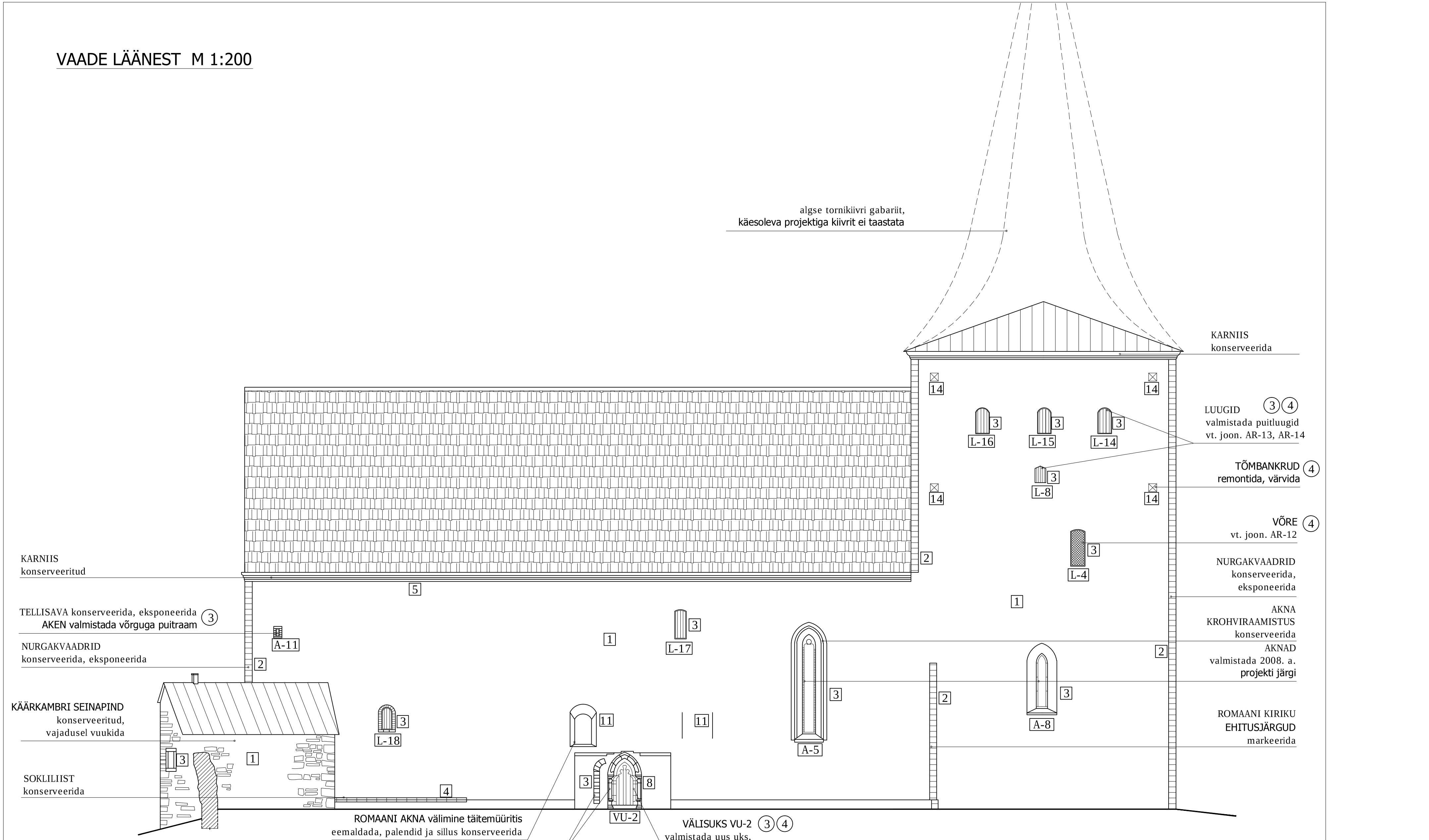
TÄHISTUSED:

- [1] säilitatavad detailid
- [A-1] avad, avatäited
- (1) värvitoon

TÖÖ: PÕIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT		JOONIS: VAADE LÕUNAST	
ARHITEKT	E. SOVA, 01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
		JOONIS AR-6	MÕÕTKAVA 1:200

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

VAADE LÄÄNEST M 1:200



MÄRKUSED:

1. Joonise aluseks on ülesmõõtmisjoonised.
2. Joonist lugeda koos seletuskirjaga.

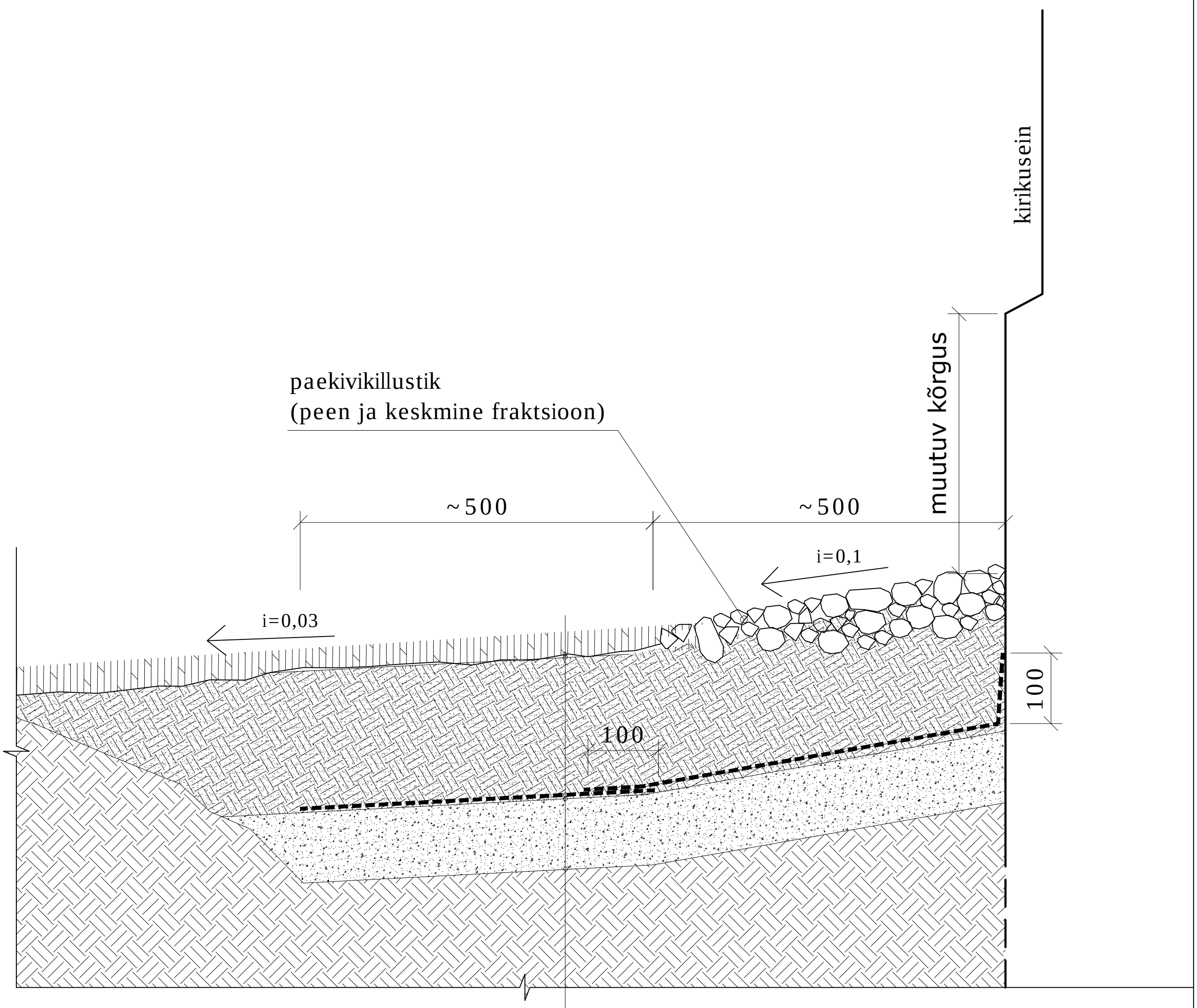
TÄHISTUSED:

- 1 — säilitatavad detailid
- A-1 — avad, avatäited
- ① — värvitoon

TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				VAADE PÕHJAST	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-7	MÕÕTKAVA 1:200

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

SILLUTISRIBA M 1:10



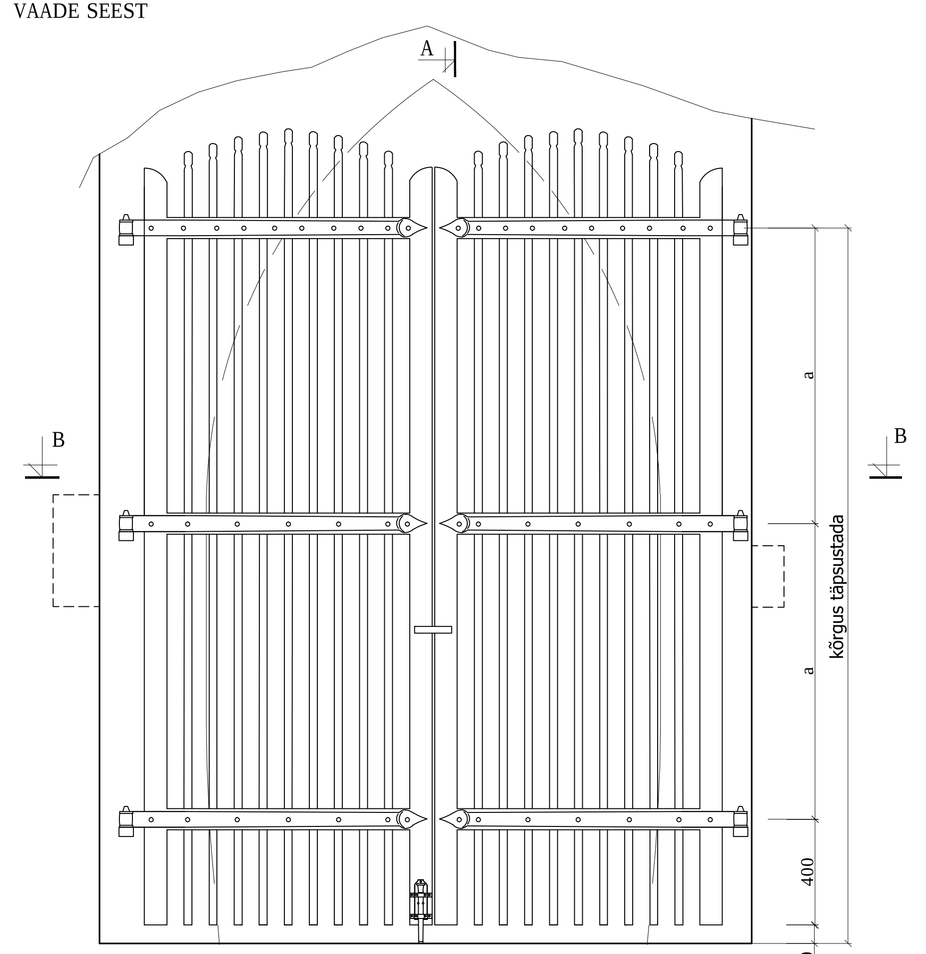
muru
tihendatud kasvupinnas 200
VOLTEX-hüdroisolatsioon-rullmatt,
(ülekate 100, seinale ülespööre 100)
tihendatud kruusliiv 100
olemasolev tihendatud aluspind

MÄRKUSED:
1. Sillutisriba ehitada joonisel näidatud languga kiriku seinast eemale.
2. Joonist lugeda koos seletuskirjaga.
3. Mõõdud antud mm-tes.

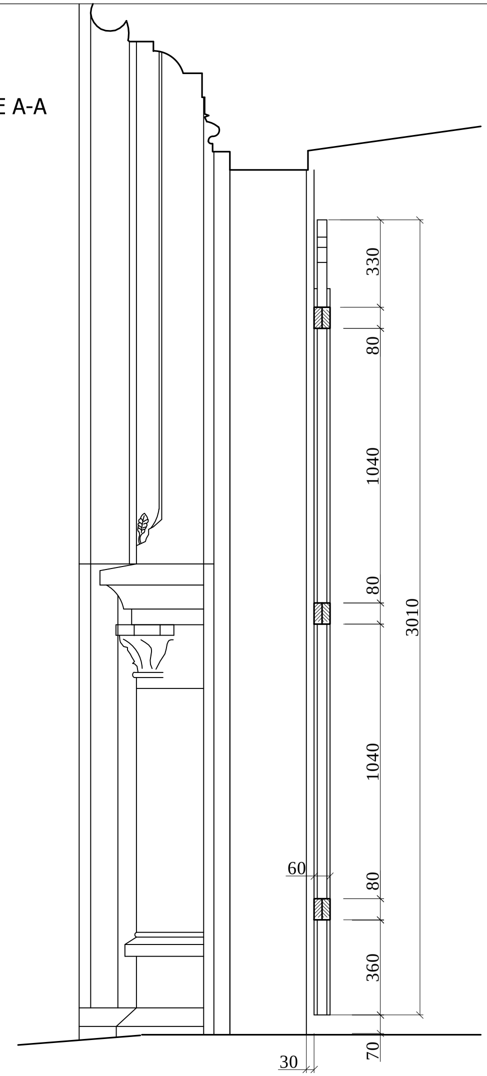
TÖÖ PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS SILLUTISRIBA	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-8	MÕÕTKAVA 1:10
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399					

LÕUNAPORTAALI TUULUTUSVÕRE TV-1   M 1:20

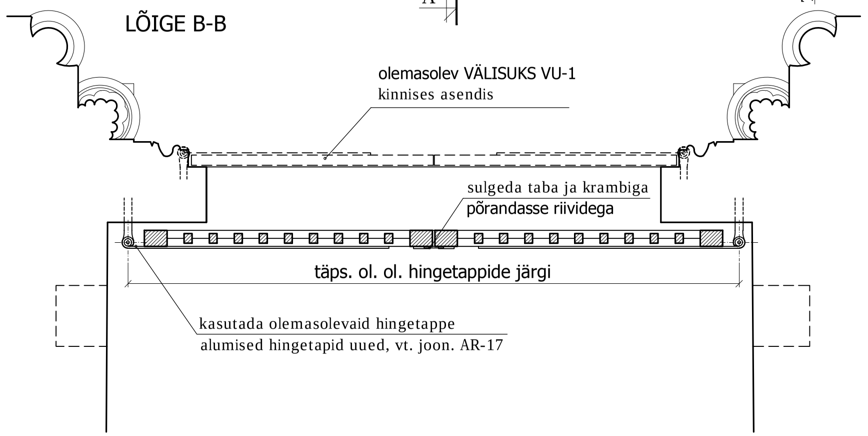
VAADE SEEST



LÕIGE A-A



LÕIGE B-B



MÄRKUSED:

1. Tuulutusvõre vajadus: 1 tk. Võre asukohta vt. joon. AR-1.
2. Materjal: okaspuit niiskusesisaldusega 12% +/-2
3. Viimistlus: linaseemne õlivärv, toon: vt. värvikaardilt p. 2.3.5.
4. Suluste vajadus:

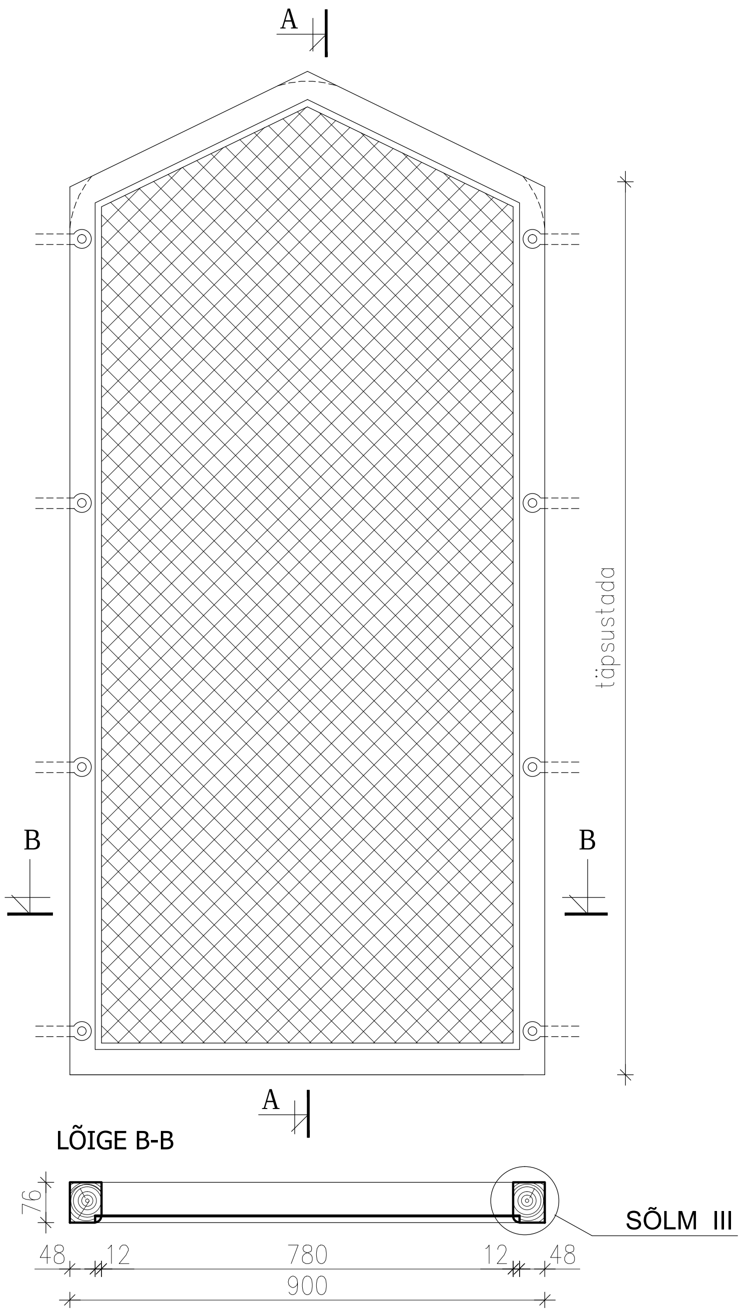
latthing	6 tk
hingetapp	6 tk (2 tk ol. olevad)
sepanaelad või sepistatud ilunaastud	
kramp	1 tk
tabalukk	1 tk
riiv	1 tk

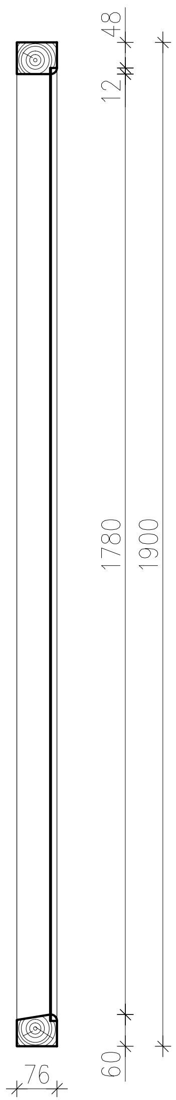
5. Mõõdud täpsustada kohapeal, ehitusliku ava järgi.
6. Hingetapp ja hingelatt vt. joon AR-16 ja AE-17, ilunaastud vt. joon. AR-18. Viimaste asemel võib kasutada sepispeaga polte.
7. Kasutada olemasolevaid sepishingetappe (puhastada roostest ja värvikihtidest). Uued hingetapid paigaldada võimalusel raidportaali vuukidesse (mõõdud joonisel soovituslikud).

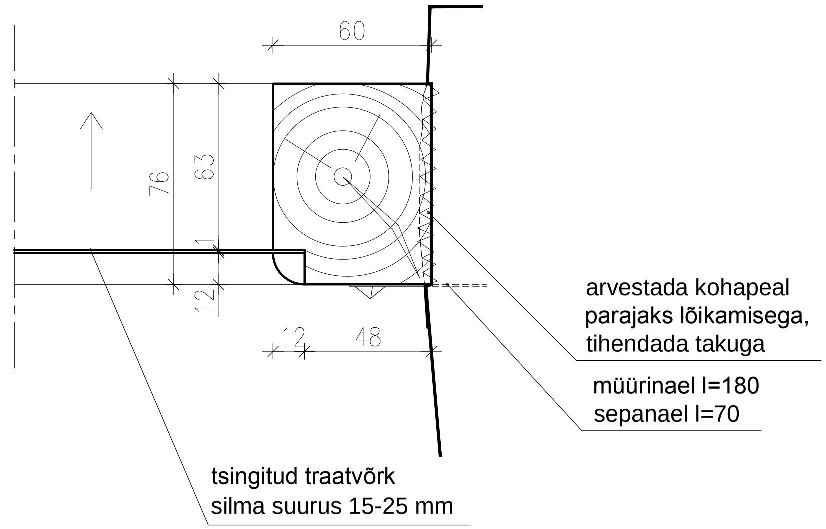
TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				LÕUNAPORTAALI TUULUTUSVÕRE TV-1	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-11	MÕÕTKAVA 1:20

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

PUITRAAMIS LINNUTÕKKEVÕRK M 1:10







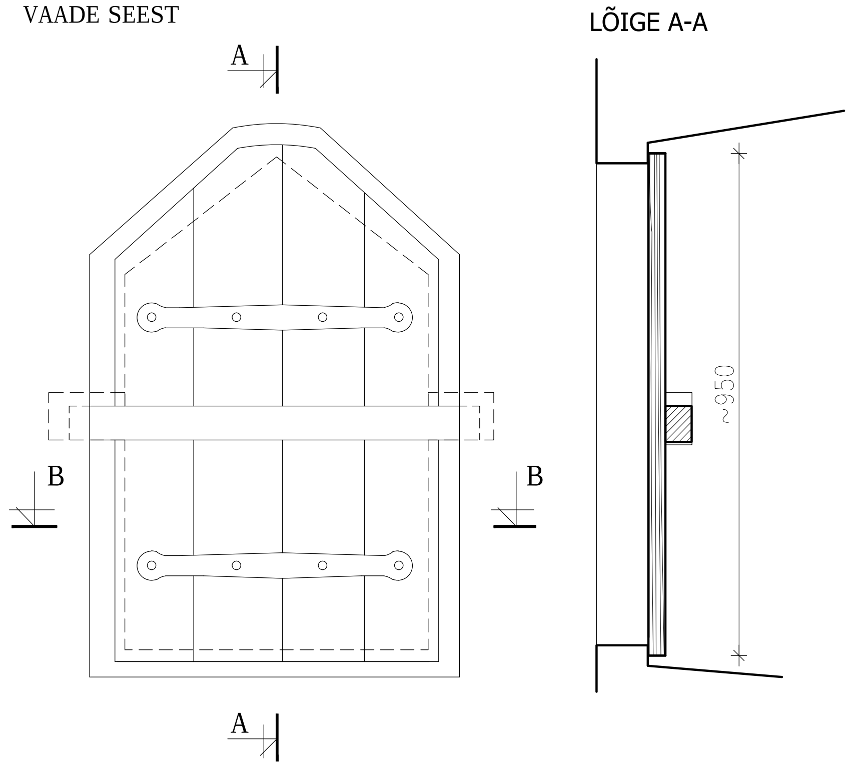
MÄRKUSED:

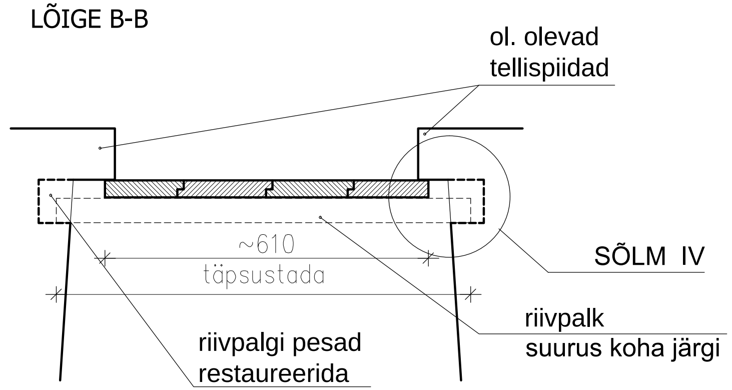
1. Linnutõkkevõrgud on projekteeritud avadesse L-1...L-4. Avade suurused on erinevad. Avade asukohti vt. joon. AR-2.
2. Materjal: okaspuit niiskusesisaldusega 12% +/-2, tsingitud metallvõrk (diagonaalne silm).
3. Viimistlus: linaseemne õlivärv (puit), metallitööde värv (metallvõrk). Toonid vt. värvikaardilt p. 2.3.5.
4. Linnutõkkevõrgud kinnitada pikkade sepistatud müürinaelaga piida siseküljel.
5. Mõõdud täpsustada kohapeal ehituslike avade järgi. Joonisel olevad mõõdud on antud L-4 täpse kiviava järgi.
6. Võrgu paigaldajal arvestada piida kohapeal parajaks tahumisega. Enne paigaldamist töödelda mahatahutud osa linaseemne õlivärviga üle. Piida ja müüriava vaheline tühimik tihendada linatakuga.
6. Piida alumine osa lõigata vihmavee parema äravoolamise tarbeks kaldu.
7. Sama skeemi järgi valmistada linnutõkkevõrgud avadesse A-11 ja A-12. Piida ristlõige valida väiksem, kinnitada sepistatud müürinaeltega.

TÖÖ PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS PUITRAAMIS LINNUTÕKKEVÕRK	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-12	MÕÕTKAVA 1:10

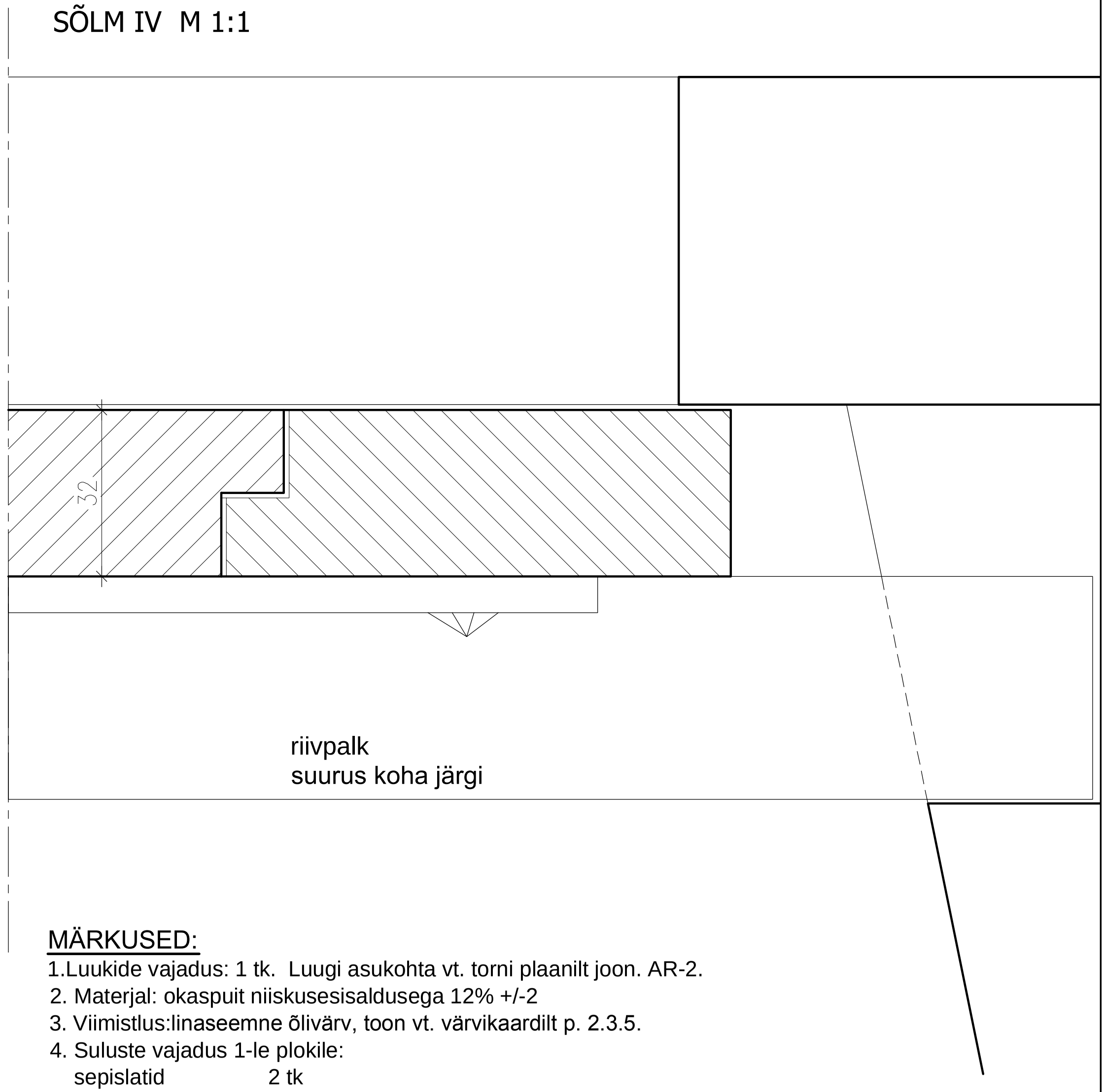
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

LUUK L-8 M 1:10





SÕLM IV M 1:1



MÄRKUSED:

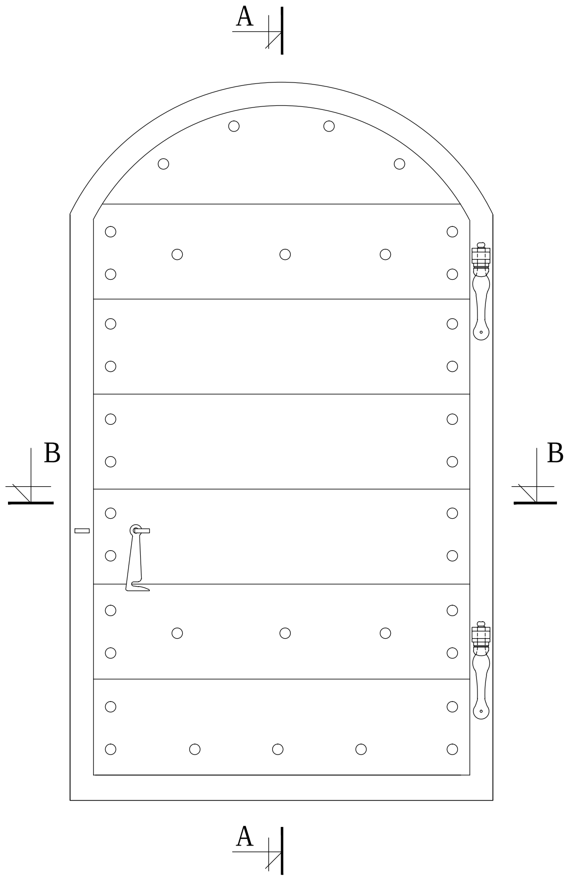
1. Luukide vajadus: 1 tk. Luugi asukohta vt. torni plaanilt joon. AR-2.
2. Materjal: okaspuit niiskusesisaldusega 12% +/-2
3. Viimistlus:linaseemne õlivärv, toon vt. värvikaardilt p. 2.3.5.
4. Suluste vajadus 1-le plokile:
   sepislatid 2 tk
   sepanaelad või sepistatud ilunaastud
5. Mõõdud täpsustada kohapeal, ehitusliku ava järgi. Joonisel olevad mõõdud on ligikaudsed.
6. Sepistatud latid valmistada vajaliku pikkusega, lati ümar lõpetus analoogne hingelatile, vt. joon. AR-19. Ilunaastud vt. joon. AR-20.

TÖÖ PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS LUUK L-8	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-13	MÕÕTKAVA 1:10

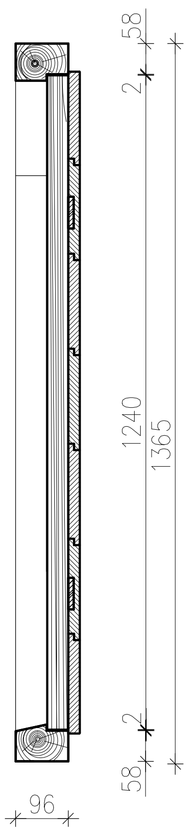
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

LUUGID L-9 ... L-16 M 1:10

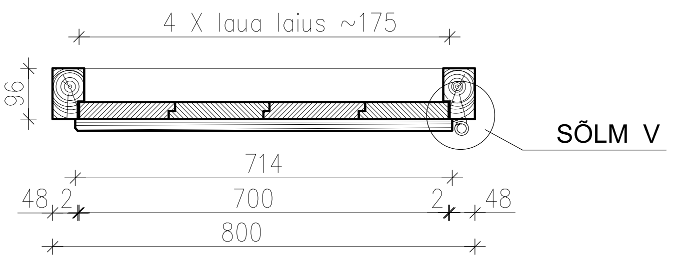
VAADE SEEST



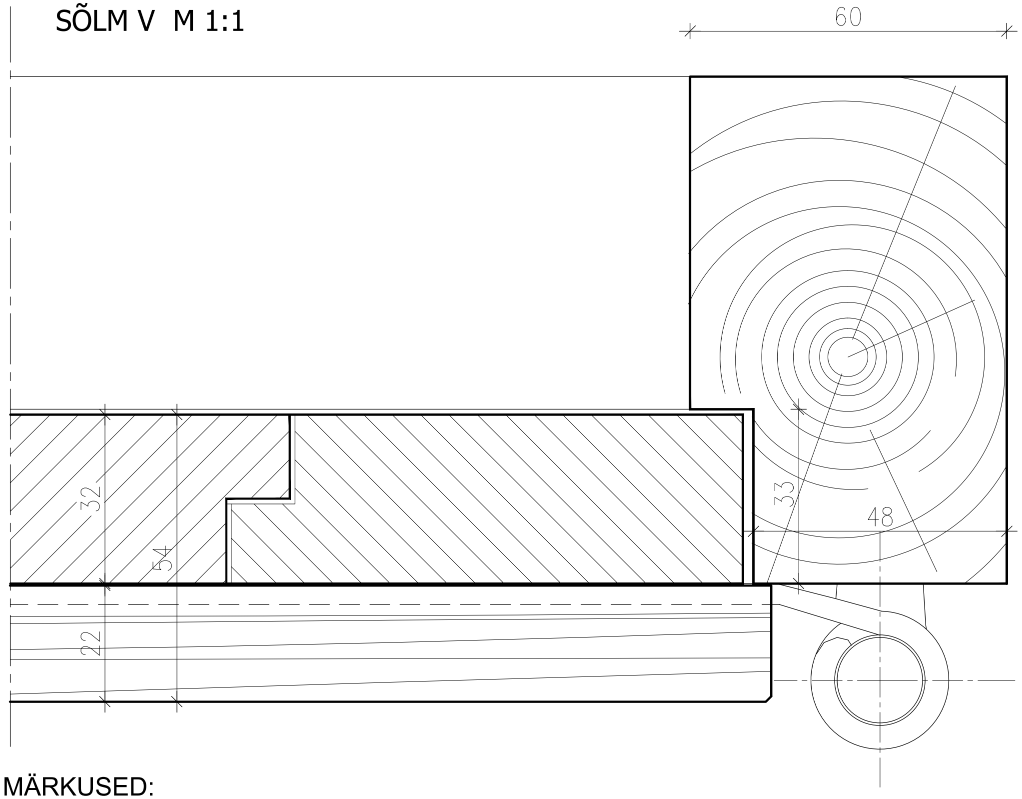
LÕIGE A-A



LÕIGE B-B



SÕLM V M 1:1



MÄRKUSED:

1. Luukide vajadus: 8 tk. Luukide asukohti vt. torni plaanilt joon. AR-2.
2. Materjal: okaspuit niiskusesisaldusega 12% +/-2
3. Viimistlus:linaseemne õlivärv, toon vt. värvikaardilt p. 2.3.5.
4. Suluste vajadus 1-le plokile:

latthing	2 tk (laua alune)
hingetapp	2 tk
sepishaak	1 tk (pikkus koha järgi)
haagi vastus	2 tk

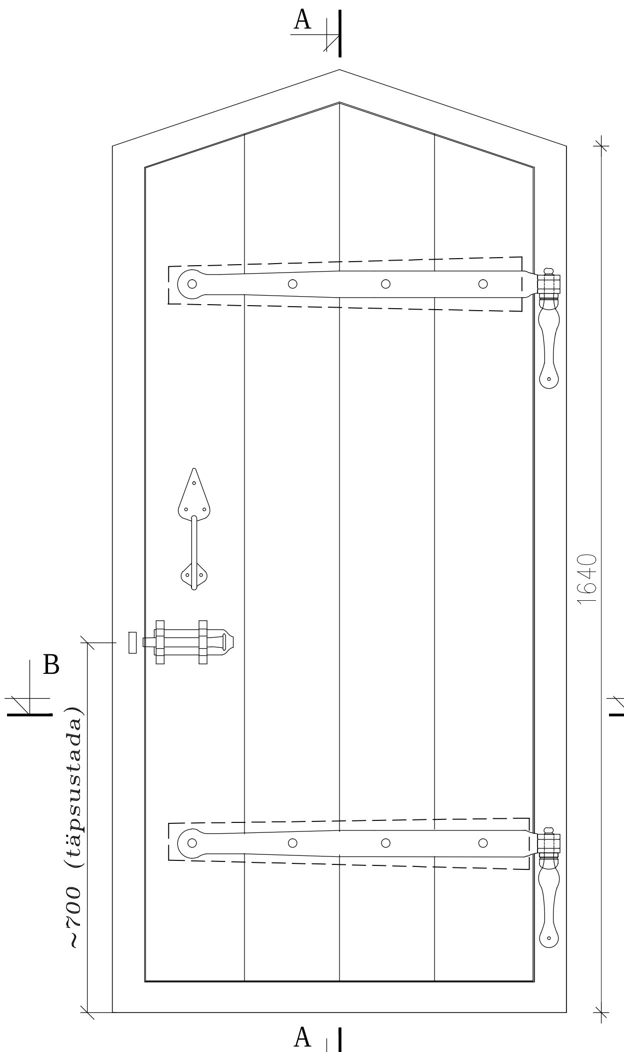
   sepanaelad või sepistatud ilunaastud
5. Mõõdud täpsustada kohapeal, ehituslike avade järgi, mis erinevad üksteisest. Joonisel olevad mõõdud on antud L-9 kiviava järgi. Luukide paigaldajal arvestada piida kohapeal parajaks tahumisega, selle võrra valmistada piidad paksemad.
6. Hingetapp analoogne uste hingetapile (vt. joon. AR-18), valmistada veidi väiksem. Hingelatt sirge lõpetusega. Haak ja haagi vastus vt. joon. AR-18. Ilunaastud vt. joon. AR-20.
7. Piida alumine osa lõigata vihmavee parema äravoolamise tarbeks kaldu.
8. Joonise järgi valmistada ka luugid avadesse L-17, L-18, L-19, vajadusel L-20. Mõõdud võtta koha järgi.

TÖÖ				JOONIS	
PÕIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				LUUGID L-9 ... L-16	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-14	MÕÕTKAVA 1:10

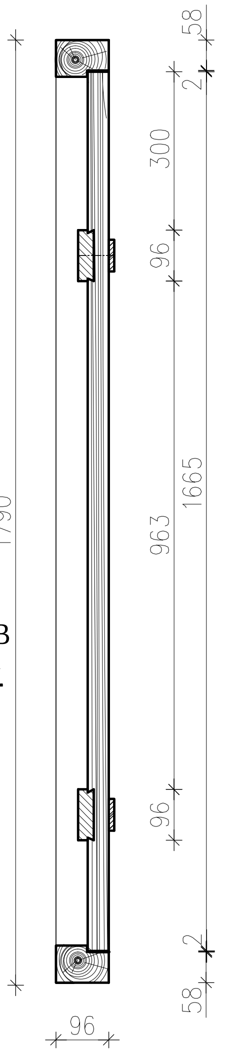
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

LAUDUKSED U-3, U-4 EI30 M 1:10

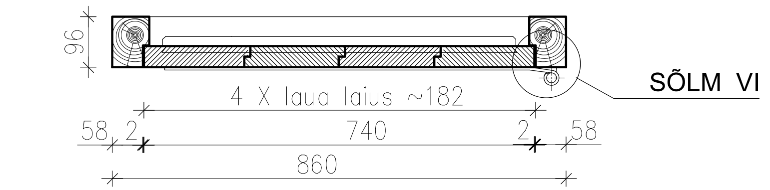
U-4 VAADE PÖÖNINGU POOLT
U-3 VAADE MÜÜRITREPILT (PEEGELPILDIS)



LÕIGE A-A

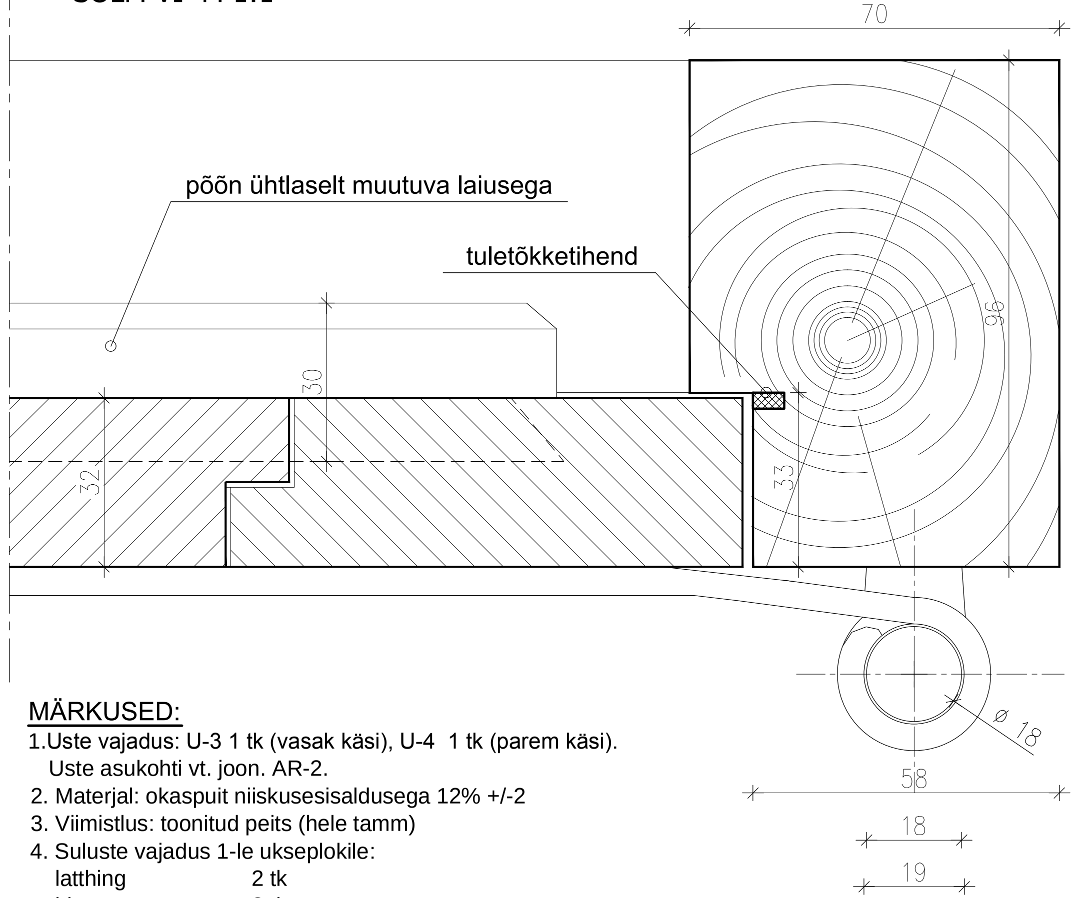


LÕIGE B-B



SÕLM VI

SÕLM VI M 1:1



MÄRKUSED:

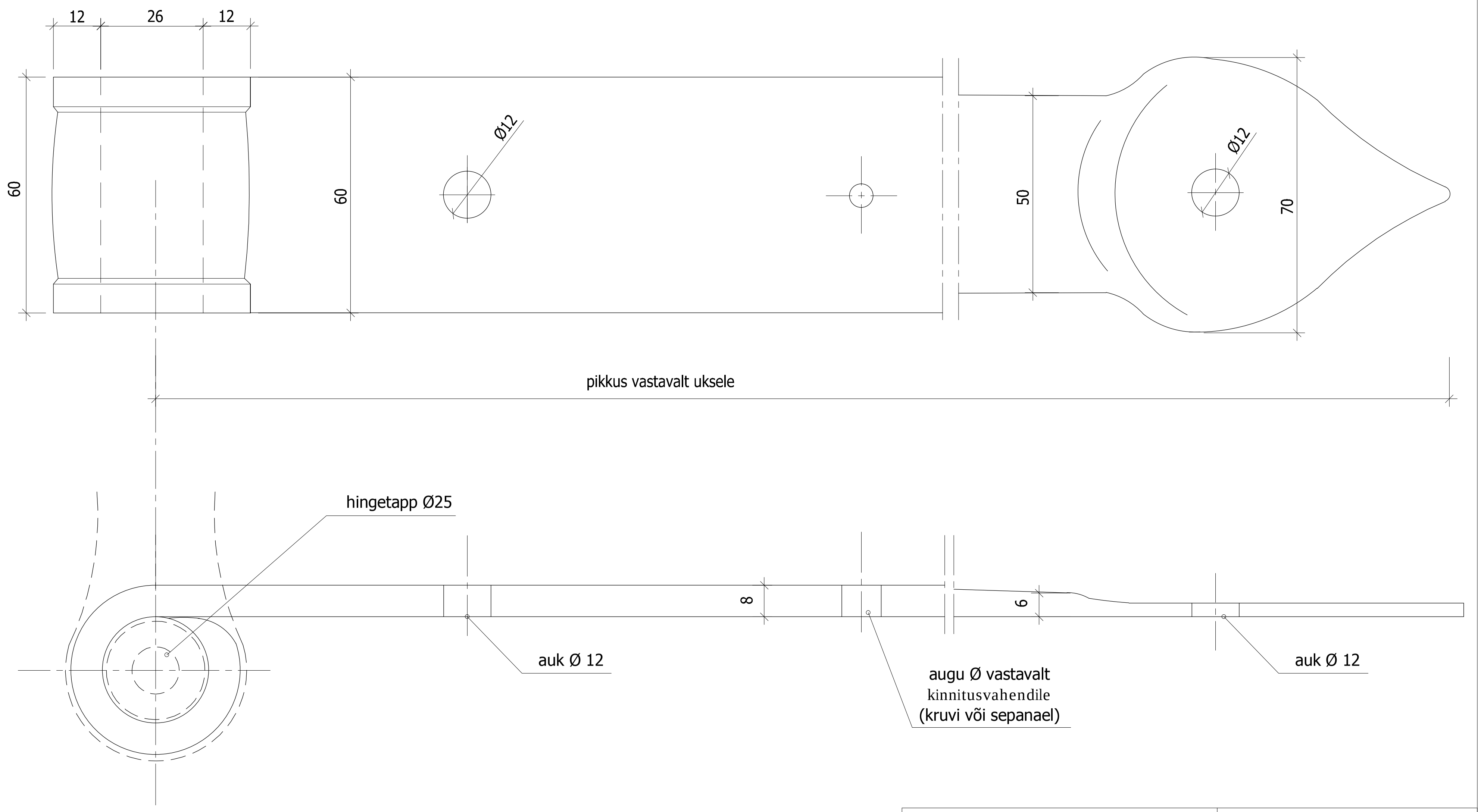
1. Uste vajadus: U-3 1 tk (vasak käsi), U-4 1 tk (parem käsi).
   Uste asukohti vt. joon. AR-2.
2. Materjal: okaspuit niiskusesisaldusega 12% +/-2
3. Viimistlus: toonitud peits (hele tamm)
4. Suluste vajadus 1-le ukseplokile:
   latthing 2 tk
   hingetapp 2 tk
   sangkäepide 2 tk
   riiv 1 kompl
   sepanaelad või sepistatud ilunaastud
5. Mõõdud täpsustada kohapeal, ehituslike avade järgi. Joonisel olevad mõõdud on antud U-4 täpse kiviava järgi. Ukse paigaldajal arvestada piida kohapeal parajaks tahumisega.
6. Hingetapp ja hingelatt vt. joon AR-18 ja AE-19, sangkäepide, riiv ja ilunaastud vt. joon. AR-20. Viimaste asemel võib kasutada sepispeaga polte.
7. Uste valmistaja tagab ukse tulepüsivusastme EI30, vajadusel kooskõlastab ukse päästeametiga.

TÖÖ: PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS: LAUDUKSED U-3, U-4 EI30	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-15	MÕÕTKAVA 1:10

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

HINGELATT UKSELE VU-2

M 1:1

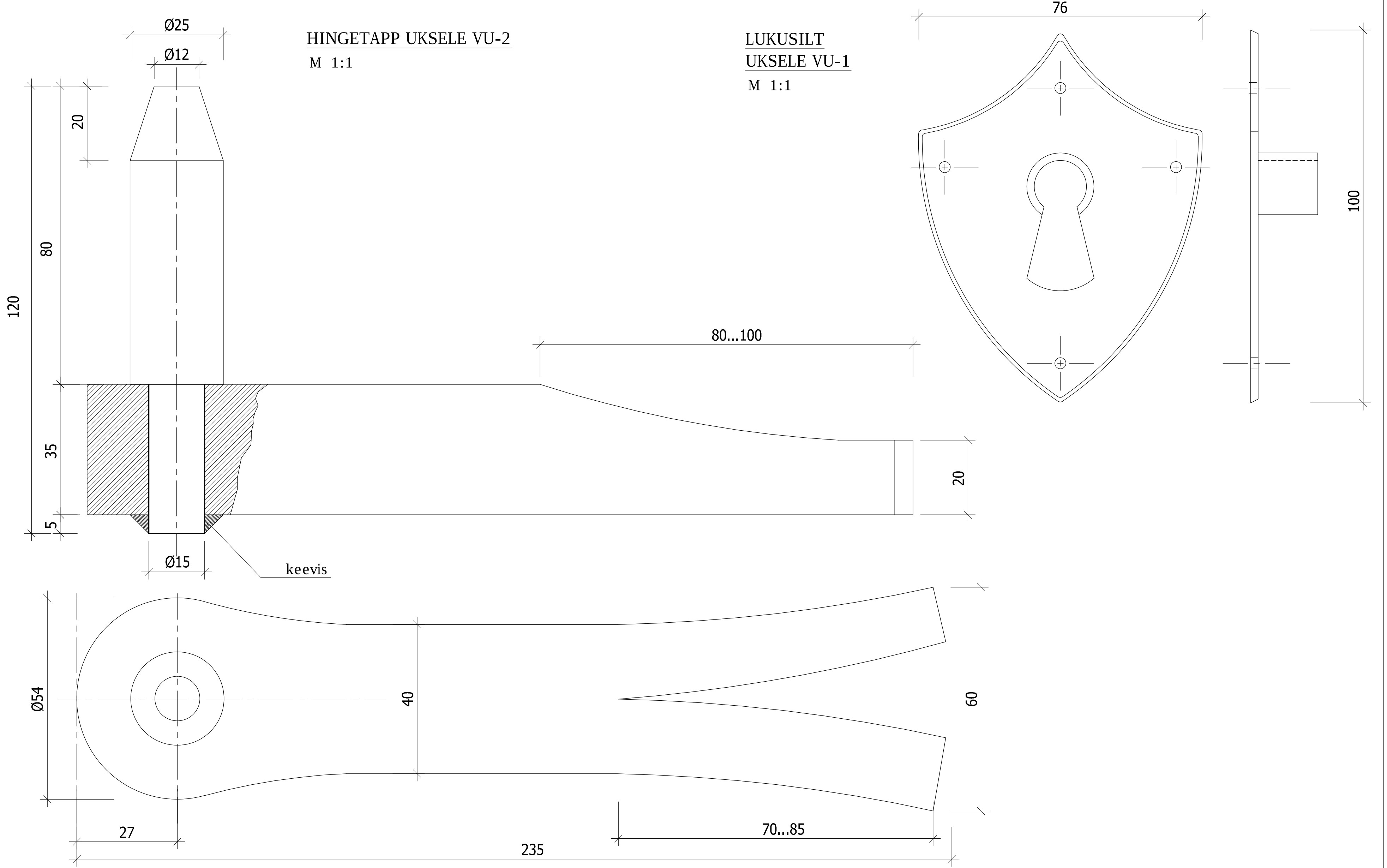


MÄRKUSED

1. Antud sepishingelatt kohandada lauduksele VU-2. Aukude läbimõõt vastavalt kinnitusvahendi tüübile. Soovitavalt kasutada kinnitamiseks suuri sepanaelu (v.a. hingetapi poolses augus, kus kasutada kruvi/polti, mis katta ilunaastuga)
2. Hingelattide materjal: teras. Pinnad sepistada.

TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				HINGELATT UKSELE VU-2	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-16	MÕÕTKAVA 1:1

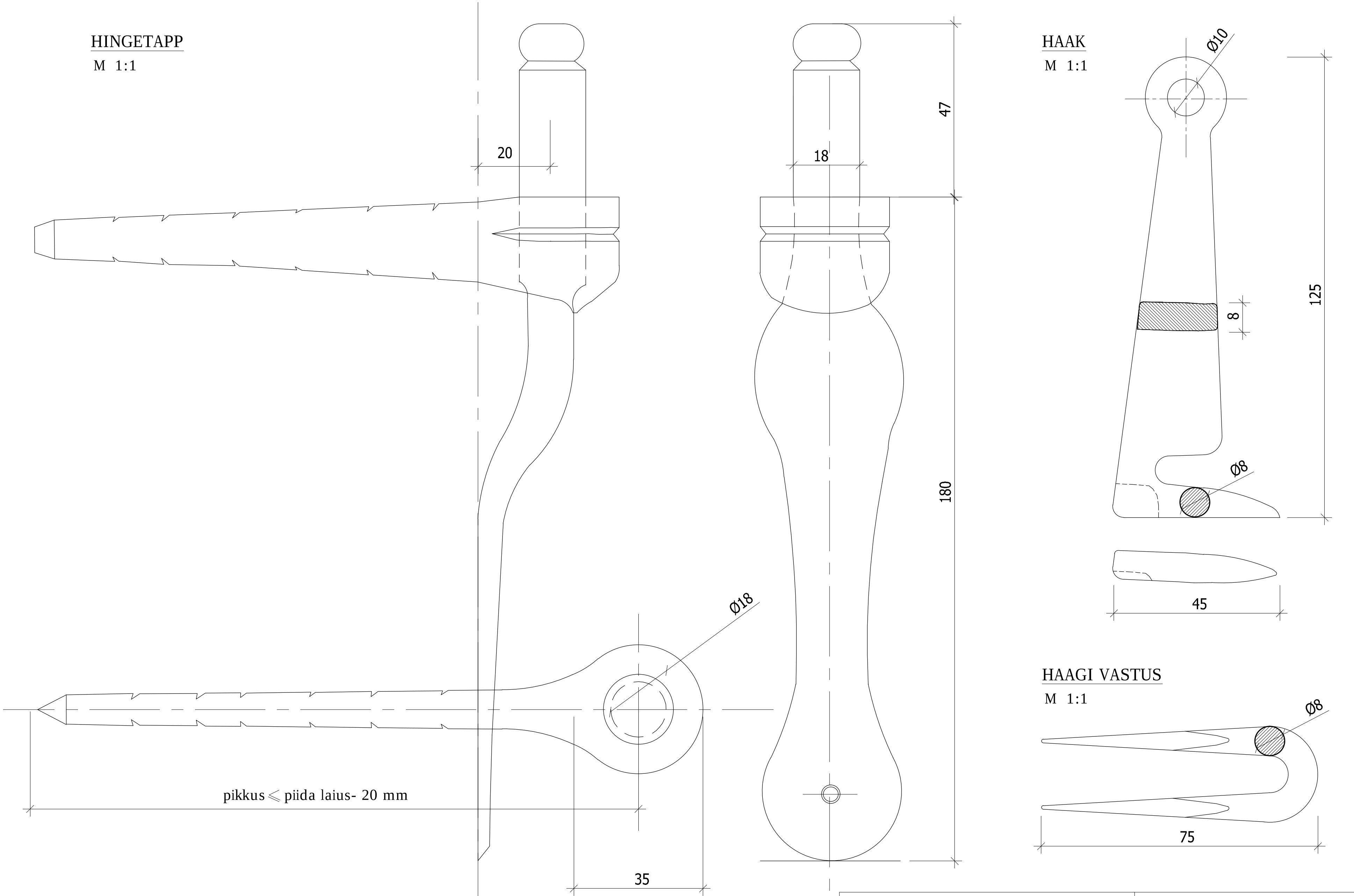
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399



MÄRKUSED

1. Antud sepishingetapp kohandada lauduksele VU-2 ja tuulutusvõredele TV-1 ja TV-2.
2. Hingetappide materjal: teras. Pinnad sepistada.

TÖÖ				JOONIS	
PÕIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				HINGETAPP UKSELE VU-2 LUKUSILT UKSELE VU-1	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-17	MÕÕTKAVA 1:1
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399					

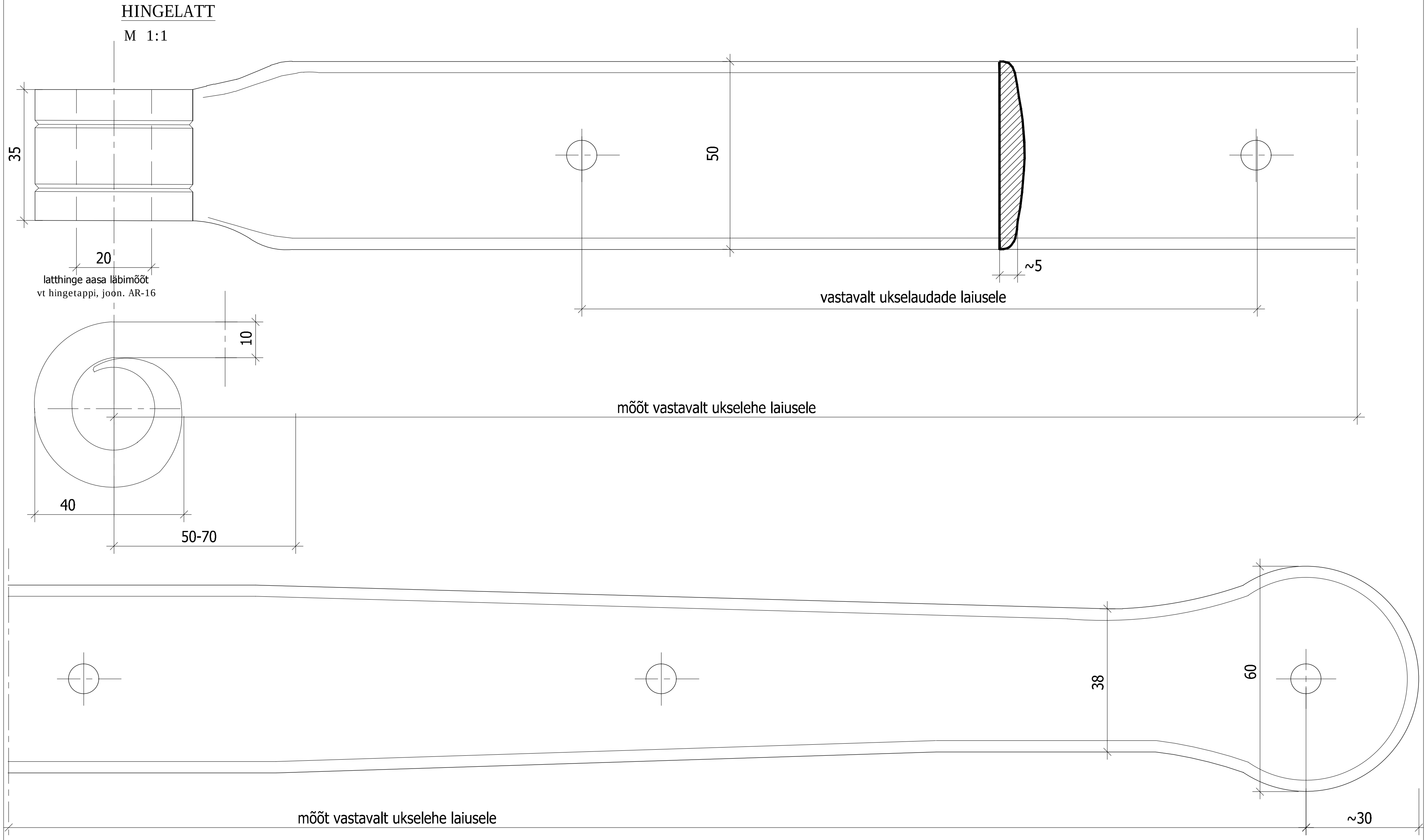


MÄRKUSED

1. Materjal- teras. Pinnad sepistada
2. Hingetapid puitustele u-3, u-4 ja luukidele

TÖÖ				JOONIS	
PÕIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				HINGETAPP, HAAK, HAAGI VASTUS	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-18	MÕÕTKAVA 1:1

RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399

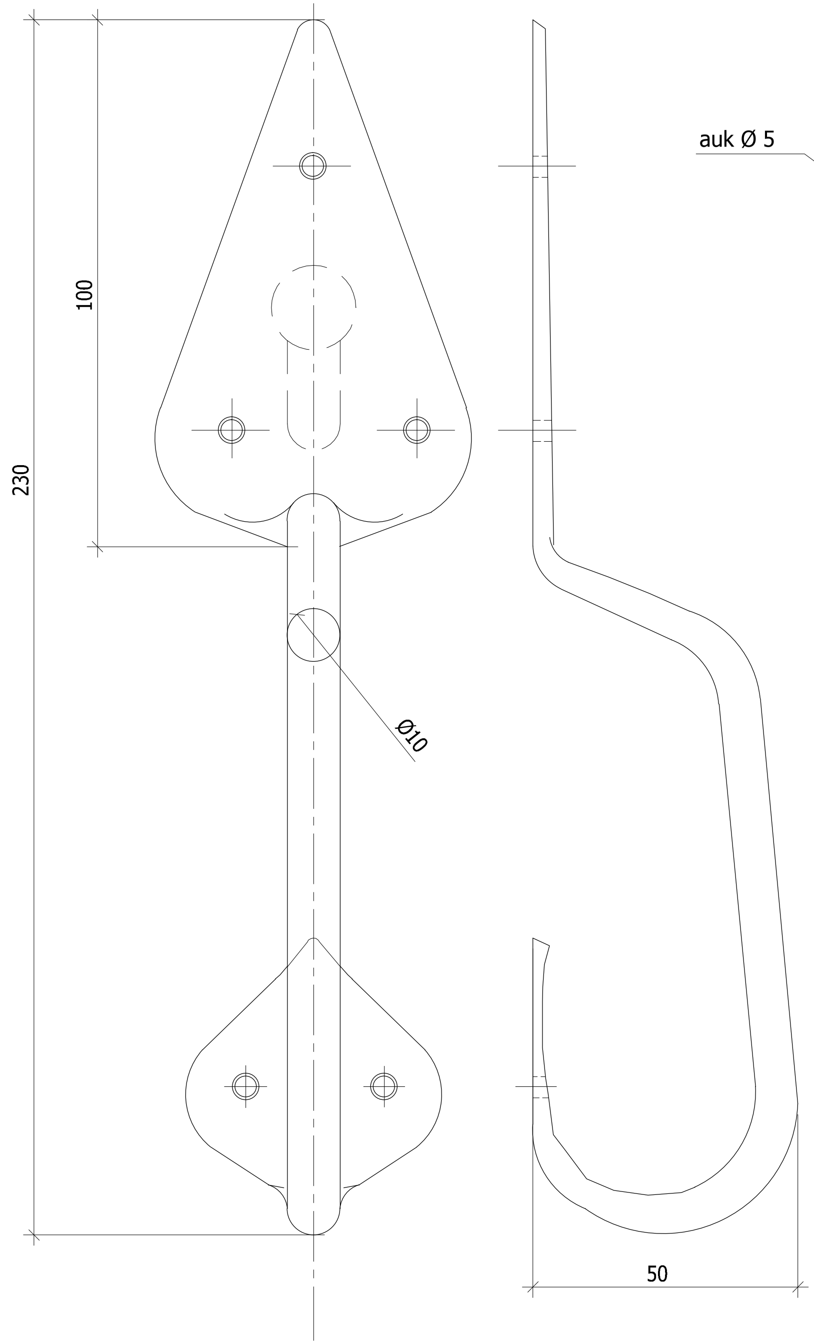


MÄRKUSED

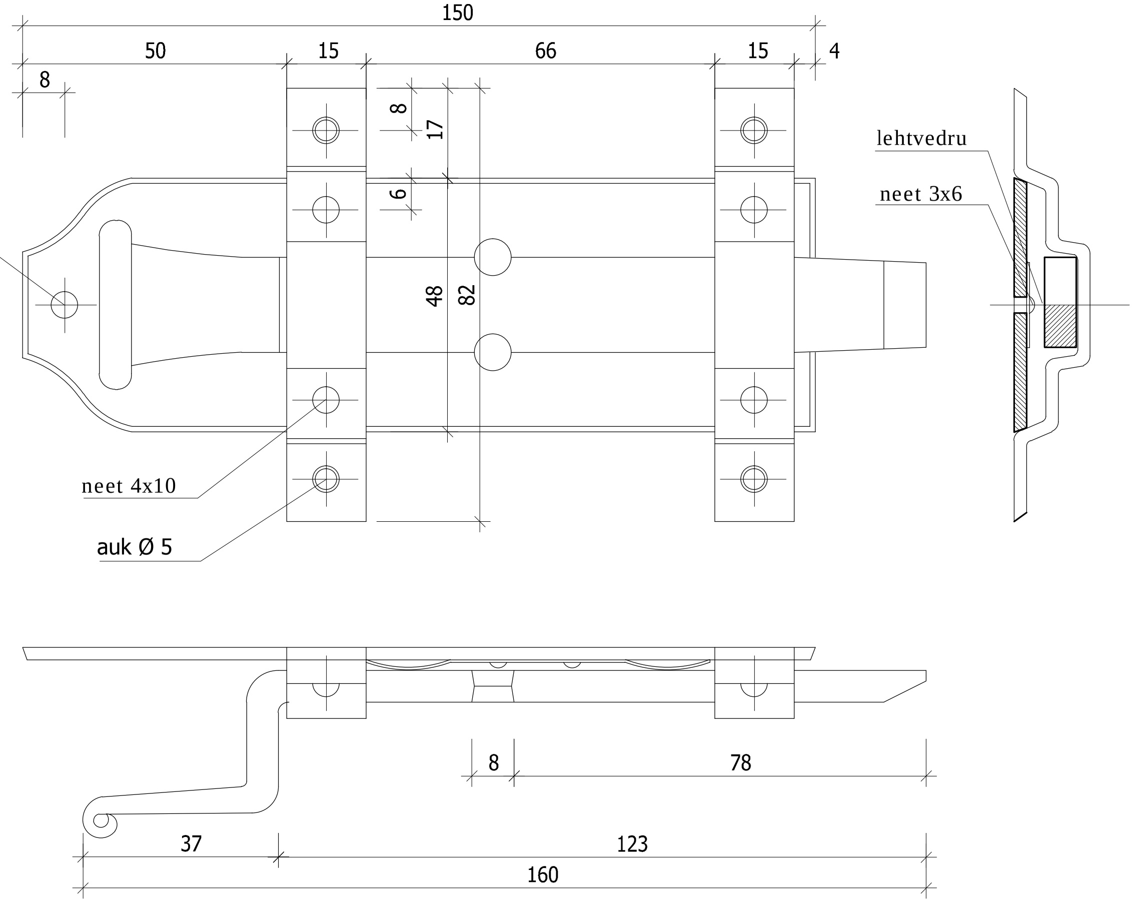
1. Antud sepishingelatt kohandada laudustele U-3 ja U-4. Aukude läbimõõt vastavalt kinnitusvahendi tüübile. Soovitavalt kasutada kinnitamiseks suuri sepanaelu (v.a. hingetapi poolses augus, kus kasutada kruvi, mis katta ilunaastuga)
2. Hingelattide materjal: teras. Pinnad sepistada.

TÖÖ				JOONIS	
PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				HINGELATT	
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT
				JOONIS AR-19	MÕÕTKAVA 1:1
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399					

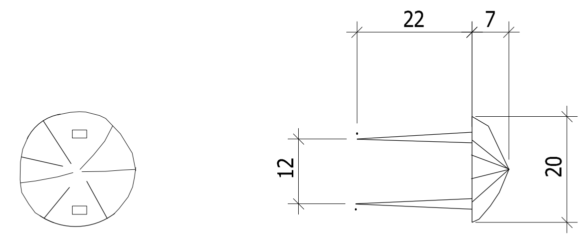
SANGKÄEPIDE
M 1:1



RIIV
M 1:1



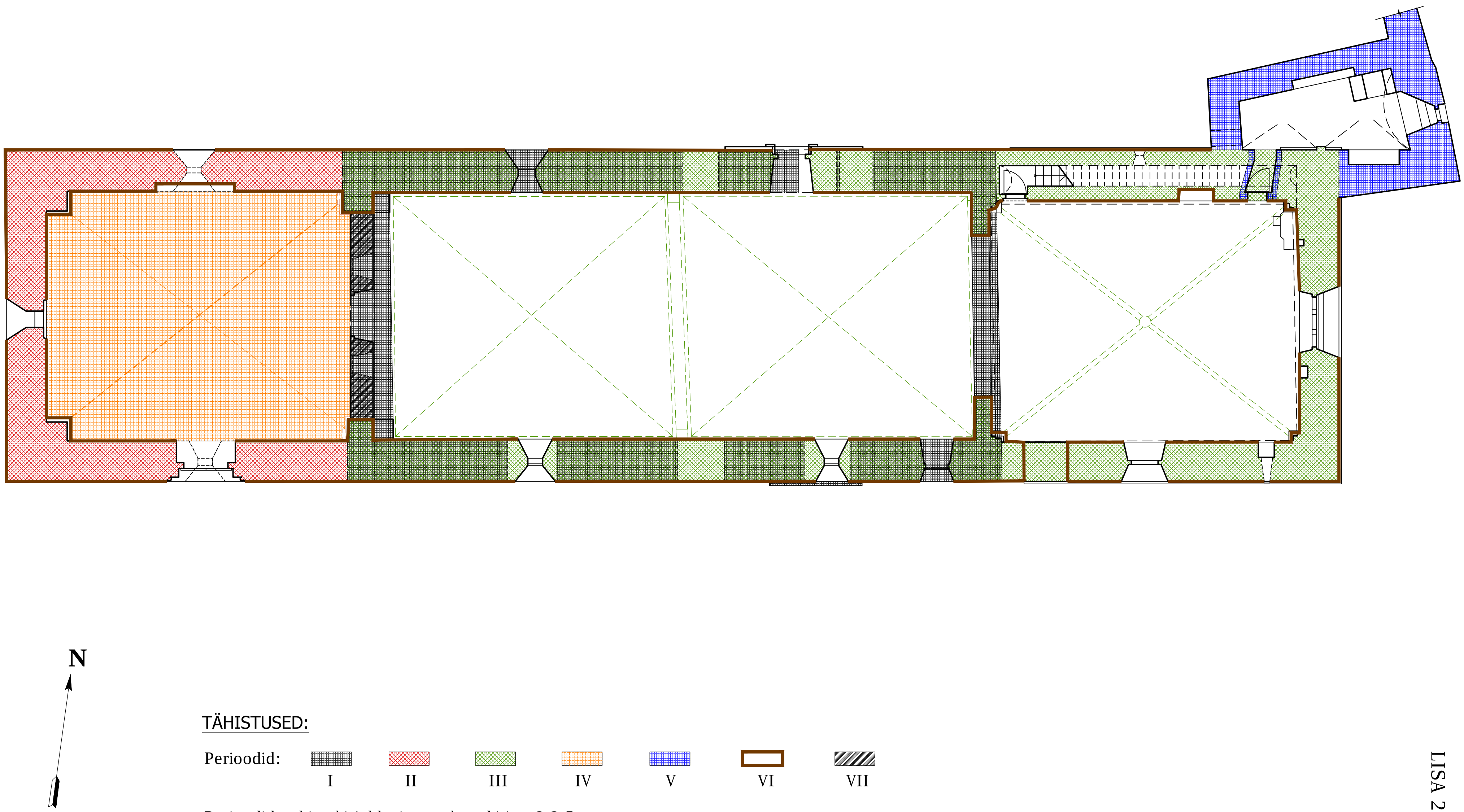
ILUNAAST
M 1:1



TÖÖ PÖIDE KIRIKU FASSAADI JA INTERJÖÖRI RESTAUREERIMISE PÕHIPROJEKT				JOONIS SANGKÄEPIDE, RIIV, ILUNAAST		
ARHITEKT	E. SOVA		01.09.13.	TÖÖ NR 13-20	STAADIUM PÕHIPROJEKT	
				JOONIS AR-20	MÕÕTKAVA 1:1	
RÄNDMEISTER OÜ. MÕÕNA TEE 15, TLN, TEL 5157157. MTR REG NR EEP000399						

LISA 2.1

PÕIDE KIRIKU OLETATAVAD AJALOOLISED EHITUSETAPID



TÄHISTUSED:

Perioodid: I II III IV V VI VII

Perioodide ehituskirjeldusi vt. seletuskiri p. 2.2.5.

3 Fotod

3.1 Pöide kiriku lõunaportaal ja välisuks väljast (foto: P. Säre)

3.2 Pöide kiriku lõunaportaal ja välisuks seest (foto: E. Sova)

3.3 Pöide kiriku põhjaportaal väljast (foto: P. Säre)

3.4 Pöide kiriku põhjaportaal seest (foto: P. Säre)

3.5 Vaade Pöide kirikule edelast