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Development of a hybrid timber and aluminum based unitized façade system resilient to the future weather conditions in Europe via monitoring campaigns and computational models

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Abstract

The StaticusCare project aims to develop a hybrid timber and aluminum unitized façade system (HUF) equipped with a predictive maintenance system (PMS) for Nordic climates, which will be based on the digital twin concept and fed by an Internet-of-Things system. The use of timber in the structure elements of the façade system aims to reduce the typical system's CO_2 footprint by 70–75 %, and the non-renewable energy consumption by 53–56 %. Nonetheless, ensuring that this novel system is durable in the Nordic current and future climate conditions is necessary. For this purpose, the HUF system will be installed in a two-floor building, monitored by a multi-sensor campaign, and replicated computationally to assess the energy use and indoor environmental quality, as well as the hygrothermal performance of the building elements for contemporary climate and under various climate change scenarios. The maintenance of the buildings with the façade system installed will be based on a PMS that is backed by an open-source python heat, air, and moisture transport (HAM) software. This one-dimensional software will be validated using a commercial one. To analyze specific problems, such as air infiltration and moisture entrapment, a two-dimensional HAM model will also be developed. In addition, building energy simulations will be performed to test several parameters affecting the indoor climate quality and energy use. Finally, the current outdoor weather files for the HAM simulations will be built based on multi-year datasets following the ISO 15927-4 methodology and the Perez model, whilst the future weather files will be based on multi-year datasets following the same methodology for two future scenarios. This multi-step methodology will allow to thoroughly test and design the HUF façade system whilst minimizing the risk, e.g., mold growth, for current and future conditions.

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1. Introduction

It has been widely recognized that pervasive changes have to be performed, at all levels of our society, to mitigate climate change and its expected negative effects, by reducing the anthropogenic greenhouse emissions drastically. This scope has led the industry and the scientific community to work on developing more environmentally friendly solutions.

In the construction sector, one of the solutions is to use, for example, building materials that are less energy intensive, such as timber (Ahmed & Sturges, 2015), and, therefore, have lower embodied energy and CO_2 emissions. Another positive aspect of timber is the fact that contrary to most of the materials used in the building construction sector, timber is a renewable material within a human lifespan. This is of the utmost importance nowadays due to the great construction levels as well as the fact that materials are a limited resource (European Commission, 2020).

Bearing all the above considerations in mind, an innovative hybrid unitized façade (HUF) system has been created in the context of the StaticusCare project (StaticusCare, 2022), financed by EEA and Norway grants. This more sustainable façade uses glulam timber to replace part of the typical aluminum frame system, while offering equivalent structural performance for this type of application. Timber has a typical embodied energy of 4.6 MJ/kg and embodied CO_2 of 0.4 tonnes CO_2/tonne (Ahmed & Sturges, 2015) and aluminum has a typical embodied energy of 201.0 MJ/kg (ca. 44 times higher than glulam timber) and embodied CO_2 of 15.1 tonnes CO_2/tonne (ca. 43 times higher than glulam timber) (Ahmed & Sturges, 2015). Hence, it is easy to understand why this is a better façade system by means of climate mitigation, aside the good mechanical, thermal capability of wood, among its other positive characteristics (Pastori et al., 2022).

In addition, since it is a unitized system, it can be quickly installed compared with traditional façade systems. This feature is extremally interesting because it has the advantage of protecting quickly the building envelope and the indoor environment from outdoor damaging sources (e.g., precipitation). Finally, the HUF system will include Internet-of-Things (IoT) sensors to be able to feed the digital twin models, which will be integrated into the building maintenance system (BMS) to safeguard the building, as well as its indoor environmental quality (IEQ).

However, due to the innovative nature of this system, it is necessary to prove that it behaves appropriately in a given climate, and that it will be able to withstand current and future conditions during its service life. The multi-step methodology, as described in the following section, has been created for this purpose. In addition, as shown by (Pastori et al., 2022), a great number of studies can be found in literature about the benefits of using a unitized system in terms of their structural behavior, but only a small number deal with their hygrothermal behavior and environmental impact. This study also intends to increase the knowledge of this type of system. Finally, this paper summarizes the multi-step methodology that will be followed to achieve the previously stated goals. More detailed information for each step can be found in these references (Coelho & Kraniotis, 2023a, 2023b; Loli et al., 2024; Ostapska et al., 2023).

2. Methodology

2.1. Step 1: Case-study with HUF system

The Hybrid Unitized Façade (HUF) system will be installed in a two-store building in order to assess its hygrothermal performance and to study the indoor climate quality. The building is located in Vilnius, Lithuania, which is classified as a humid continental climate with a Köppen classification of Dfb (Kottek et al., 2006). Vilnius has a humid and cold winter, where the temperatures are frequently below zero, and a humid and warm summer, while it has a moderate precipitation throughout the year.

The existing building façade (Figure 1a), which has a northeast orientation, will be replaced by the HUF system (Figure 1b). The HUF is composed by three different zones, namely: Section A) Opaque zone – bent tin sheet, mineral wool insulation, enameled glass (U-value = 0.13 W/(m^2K) (Coelho & Kraniotis, 2023b)); Section B) Frames – made from glue laminated timber beams and aluminum (U-value = 0.38 W/(m^2K) (Coelho & Kraniotis, 2023b)); and Section C) Transparent zone – triple glazed glass unit (U-value = 0.50 W/(m^2K) (Coelho & Kraniotis, 2023b)).

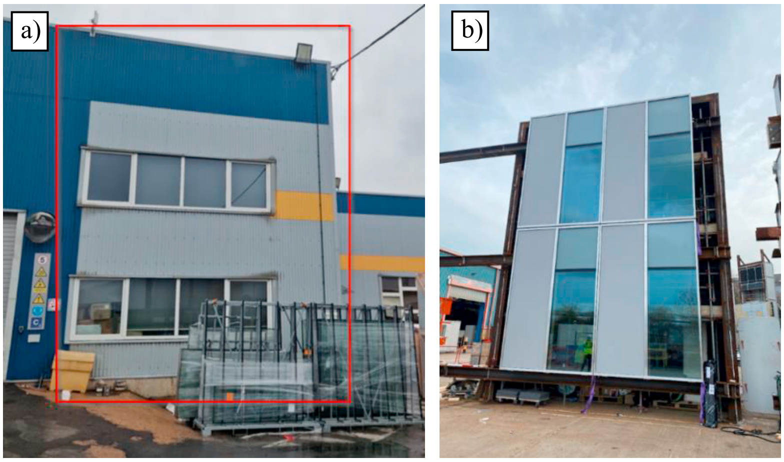

Figure 1 – Building where the HUF system will be installed and monitored (a) and example of four units of HUF system (b)

2.2. Step 2: Monitor the case-study

The monitoring campaign that will be installed in the case-study will act at three different levels, namely: 1) indoor climate, 2) surface and interior HUF and 3) outdoor climate.

The *indoor climate* will be monitored firstly to assess the quality of indoor climate (with and without the HUF system) in terms of thermal comfort, visual comfort, indoor air quality and energy consumption. Objectively, the following indoor parameters will be measured at different locations and heights, namely: 1) air temperature, 2) relative humidity of air, 3) mean radiant temperature, 4) air velocity, 5) illuminance, 6) CO_2 and 7) total VOC.

These values can also be used to build spatial interpolation-based maps, which allow the assessment of the indoor climate quality to perform the necessary changes, if need be (e.g. (Yu et al., 2021)). Subsequently, registered data – air temperature and relative humidity – will be used as inputs for the one-dimensional model. This data will also be used for model calibration for the whole-building models, i.e., WUFI®Plus and IDA ICE.

The conditions in the *interior of the HUF system* and *in their surface* will be used to both assess the hygrothermal performance of the HUF system, and to calibrate the one-dimensional models. The hygrothermal performance of the HUF will be assessed in terms of: 1) mold growth, 2) surface and interstitial condensation risk, 3) air permeance and 4) transient U-value. Subsequently, the following parameters will be measured at different locations of the façade, namely: 1) temperature, 2) relative humidity, 3) moisture content and 4) air infiltration.

Finally, the *outdoor climate* in the vicinity of the case-study will be monitored using a complete outdoor station that will measure, at least with hourly frequency, the following meteorological parameters: 1) air temperature, 2) relative humidity of air, 3) air pressure, 4) global radiation, 5) diffuse radiation, 6) long-wave counter radiation, 7) precipitation, 8) wind direction and 9) wind speed. These values will be used to explain the indoor behavior, and to build the necessary weather files for simulations, e.g., .wac file for WUFI and .try file for IDA ICE. Finally, the CO_2 and total VOC will also be monitored outdoors to establish relationships with the respective indoor climate measurements.

2.3. Step 3: Building modelling

The building modelling will be performed by two different types of strategies, namely: SketchUp and Revit. In WUFI®Plus, the geometry of the building can be developed externally by one of these two software. SketchUp allows for a rapid generation of complex geometry. Revit, on the other hand, can be coupled with other stages of designing and constructing the building, i.e., via BIM, as well as being coupled to a LCA software (subsection 2.4), despite being more complex to use. In addition, the geometry in IDA ICE can also be generated and imported from REVIT.

Aside from the geometry of the case-study, other parameters are also of key importance for the hygrothermal behavior of the building, namely the internal gains. These gains are usually due to the occupants' use of the building, and it is accounted by considering the gains due to human, equipment, and lighting system. In Norway, this is normally accounted by means of the day-profiles that exist in the Norwegian specification (SN-NSPEK 3031, 2021), which are building typology dependent. Note that in accordance with the software used, this day-profile loads might have to be transformed (Coelho & Kraniotis, 2023b). For the case-study, specific day-profiles for both monitored rooms will be built.

2.4. Step 4: Building performance simulation

The building performance simulation will be developed at two levels, namely: 1) hygrothermal performance, and 2) environmental impact assessment. The first level is subdivided into three sections, i.e., one-dimensional (using WUFI®Pro and HAMOPY), two-dimensional (using WUFI®2D) and whole-building simulation (using WUFI®Plus and IDA ICE). The second level corresponds to a cradle-to-grave life cycle assessment (LCA) using OneClickLCA.

The latter assessment is one of the bases of the StaticusCare project since it aims to produce a less polluting system by means of using a hybrid system, in which part of the traditional aluminum frame is replaced by timber. This step will be based on the quantity of materials used to build a unit of the HUF system and the respective environmental product declarations (EPDs). In addition, a comparative LCA will be performed between the conventional system (i.e., aluminum frame) and the hybrid system (i.e., timber and aluminum frame), which will be structural and thermally equivalent systems, to quantify the reduction of the CO_2-eq. emissions by means of replacing aluminum with timber.

The aim of using the HAMOPY, a python-based HAM software, is to integrate it into the building maintenance system (BMS), which is possible due to its high flexibility. Firstly, this software has been compared against the commercial software, WUFI®Pro (Ostapska et al., 2023), which has been extensively validated in various different conditions (Coelho & Henriques, 2023), for the assembly sections (Coelho & Kraniotis, 2023a). However, due to the façade configuration, the one-dimensional simulations, which due to their fast simulation speed can be successively incorporated into BMS, will have to be adapted from the two-dimensional results by means of the sections that will be run or by means of including heat/moisture sources. In addition, the most probable risk spot locations in the assemblies were identified through a two-set procedure: 1) a workshop with SINTEF researchers who have extensive experience with moisture in constructions, and 2) a questionnaire that was directed to facility managers in Scandinavian countries (Loli et al., 2024).

The whole-building simulation models – WUFI®Plus and IDA/ICE – will be used to obtain specific indoor conditions for the locations (see subsection 2.5) in which the indoor climate will not be measured. This software will also be used to assess the indoor climate and the energy consumption for the different locations that will be run considering climate change (see subsection 2.5). Finally, these models will be used in the final step of the project to build a building physics digital twin of the case-study to be used to ensure an optimal indoor climate for its occupants, but also ensure the longevity of the building through its service life.

2.5. Step 5: Weather/climate files

For current conditions, the measured data of temperature (°C), relative humidity (%), air pressure (hPa), global radiation (W/m^2), precipitation (mm/a), wind direction (°) and wind speed (m/s) for Oslo, Trondheim and Tromsø were downloaded from the *Norwegian Centre for Climate Services* (NCCS, 2022). Initially, thirty years of data – 1990-2019 –were downloaded for each previously mentioned meteorological parameter and each location. However, since the hourly data was only measured from 1992 for Oslo, 1996 for Trondheim and 1998 for Tromsø, the periods were limited respectively to 27, 23 and 21 years' of data (Coelho & Kraniotis, 2023b), which are still valid for the performed assessments.

An user independent code was developed to find and fill the existing weather data gaps (Coelho & Kraniotis, 2023b). These wide ranges of data were transformed into test reference years (TRY) by means of using the methodology of standard (EN ISO 15927-4, 2005). The global radiation was divided into its diffuse and direct parts using the DIRINT model (R. Perez et al., 1990; R. R. Perez et al., 1992). Finally, the .wac files were created. All these procedures are performed using the authors' developed code (Coelho & Henriques, 2021; Coelho & Kraniotis, 2023b).

Subsequently, part of the same procedure will be applied to build the future weather files. For that, the meteorological parameters will be downloaded from the CORDEX online database (CORDEX-2, 2019). This process will be followed for two Representative Concentration Pathway (RCP) climate change scenarios – i.e., RCP 4.5 (an intermediate GHGs emission scenario) and RCP 8.5 (and a high GHGs emission scenario) (Climate Change - SPM, 2014) – for the near-future (NF, 2035–2064) and far-future (FF, 2065–2094). The goal is to simulate the assembly under different types of European climates, namely, oceanic climate, continental climate, Mediterranean climate and arctic climate, and to see the differences and optimize the assembly in accordance.

3. Results

The development of the digital twin models of the case-study is the culmination of the whole-project (Figure 2). These models will be a part of the BMS that will be updated in real-time from the integration of the monitored data from the case-study (Figure 2). Consequently, facility managers can keep track of the building's hygrothermal and building physical status and thus, reduce future rehabilitation costs. It also enables identifying critical conditions for the building itself (i.e., risk spots), as well as for the indoor environmental quality (IEQ) by means of recognizing problems in the building physics scope. These can be, e.g., an indoor temperature lower than setpoint temperature due to a faulty HVAC system or interstitial condensation within the assembly, to name a few.

The development of this innovative multi-field methodology is time-consuming since it is based on information from a variety of different scientific fields. Having this in mind, by developing a code specifically for that purpose and using tools in the methodology that can be efficiently connected, its application to other buildings in the future will be a much more straightforward and quick process.

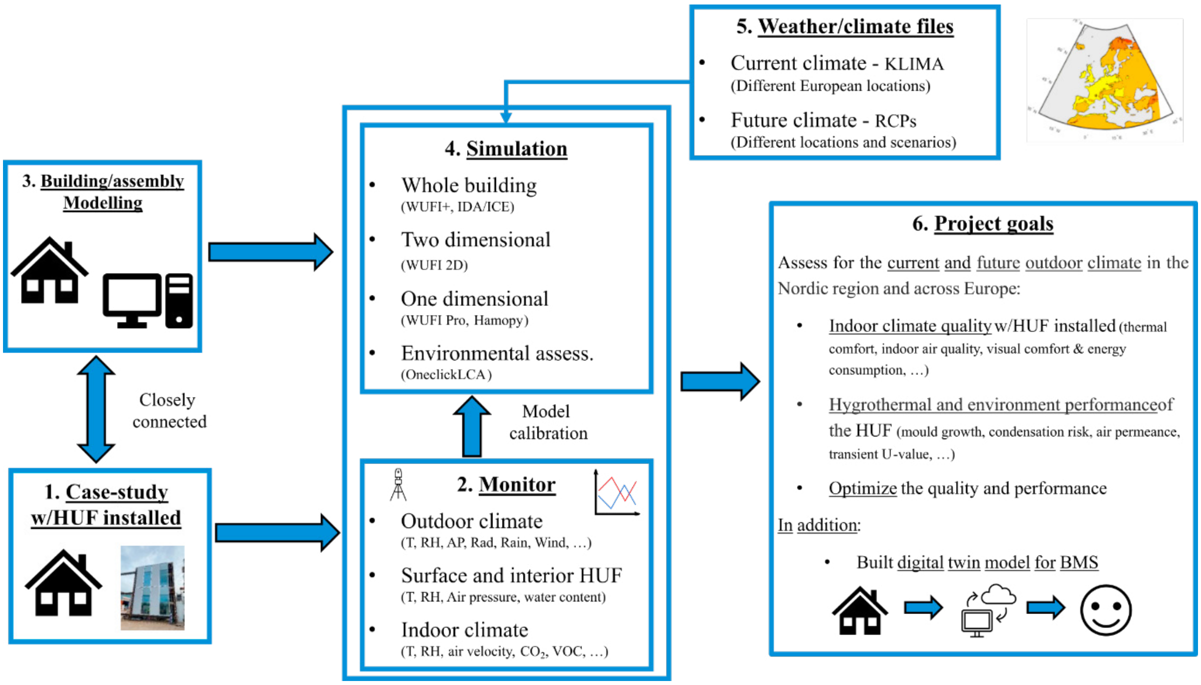

Figure 2 – Overall methodology of the StaticusCare project

4. Conclusions

This paper presents the methodology for the StaticusCare project concerning the development of a more sustainable and less-polluting aluminum and timber unitized façade system that can withstand current and future weather conditions. In addition, this façade system will have integrated IoT sensors so that its preservation can be incorporated into the building management system. This feature will be achieved by means of creating digital twin models of the real building, which will be fed by the data measured by the IoT sensors. Finally, these models will be used to assess the building's current state and, in case it is necessary, propose improvement measures.

This methodology will be based on a long-term and multi-sensor monitoring campaign of a real building with the HUF system installed and on the computational modelling of the building by multi-purpose software. Overall, the methodology comprehends six main steps, namely: 1) Build the case-study; 2) Monitoring campaign; 3) Case-study modelling; 4) Case-study performance simulation; 5) Weather/climate files; and 6) Build digital twin. This multi-step methodology will be applied in the future, either partially or globally, to real façade construction projects.

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