SUSTAINABLE DEVELOPMENT IN LISTED DISTRICTS: CO2-NEUTRAL WORLD HERITAGE SPEICHERSTADT HAMBURG

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Abstract

To achieve Germany's 2045 climate-neutral building stock goal, the integration of renewable energies in retrofitting is necessary. The CO2-neutral Speicherstadt Hamburg project in the historic warehouse district focuses on sustainable heat supply in listed buildings. The project consists of two main approaches: a practical approach combining historically sensitive components for heat supply, creating a comprehensive energy renovation concept with renewable energies in the listed area, and a methodological approach using Building Information Modeling (BIM) to integrate various simulation models and centralize outcomes efficiently. This enables a holistic and energy-efficient retrofit, addressing flow-specific, thermal, and ecological aspects, marking a significant step toward a CO2-neutral listed building stock.

Kurzfassung

Um das Ziel eines nahezu klimaneutralen Gebäudebestands in Deutschland bis 2045 zu erreichen, ist die Integration erneuerbarer Energien bei einer Sanierung entscheidend. Das Projekt CO2-neutrale Speicherstadt Hamburg im historischen Speicherstadtviertel ist auf nachhaltige Wärmeversorgung in den denkmalgeschützten Gebäuden fokussiert. Das Projekt umfasst zwei Hauptelemente: einen praktischen Ansatz, der aus denkmalpflegerischer Sicht akzeptable Komponenten für die Wärmeversorgung nutzt und damit ein Energiekonzept mit erneuerbaren Energien im Denkmalbereich schafft. Der methodische Ansatz verwendet Building Information Modeling (BIM), um verschiedene Simulationsmodelle zu integrieren und Ergebnisse zu zentralisieren. Dieses Vorgehen legt die Grundlagen für eine ganzheitliche, energetische Sanierung unter Berücksichtigung von flussspezifischen, thermischen und ökologischen Aspekten – ein bedeutender Schritt zum CO2-neutralen, denkmalgeschützten Gebäudebestand.

Introduction

In Germany, the target is to achieve a nearly climate-neutral building stock by 2045 (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2019). That is why the Chamber of Commerce has set itself the goal of making Hamburg a climate-neutral city by 2040 (Handelskammer Hamburg, 2021), which of course also includes the world heritage site 'Speicherstadt Hamburg'. A large proportion of anthropogenic greenhouse gas emissions are attributable to the combustion of fossil fuels for energy production. For this purpose, the use of renewable energies will be indispensable, and their share of the heat supply has to increase significantly in the coming years - using renewable energies is a promising alternative to burning fossil fuels in terms of greenhouse gas emissions. To achieve this, the building stock must be developed sustainably. Key players are increasingly focusing on energy concepts in the building sector to optimize building operation. Therefore, the primary energy demand in Germany is to be drastically reduced by up to 80 percent compared to 2008 through a combination of energy savings and the use of renewable energies (European Commission, 2020). To this end, it is also intended to double the retrofitting rate of the existing building stock from 2020 to 2030 to significantly reduce emissions (Bundesregierung, 2020). The retrofitting measures are not limited to the provision of energy. The aim is to achieve holistic concepts that consider a reduction in energy requirements, e.g. through improved thermal resistance of the outer shell, as well as the integration of innovative components with which renewable energy can be generated, stored, and utilized locally.

This paper presents a joint project that aims to contribute to precisely these objectives by focusing on a holistic approach. The goal is to achieve a near climate-neutral energy supply through structural retrofitting and plant modernization measures that are ecologically justifiable from the point of view of monument protection and through innovative energy supply concepts. These concepts require the incorporation of a locally available supply of renewable energies. This holistic approach with the necessary technologies and concepts is being implemented using Hamburg's Speicherstadt as an example, with a key emphasis on utilizing a BIM (Building Information Modeling) model as the central hub for data exchange.

The 'Hamburg's Speicherstadt'

Hamburg's Speicherstadt is the world's largest contiguous ensemble of blockhouses recognized and protected by the Hamburg Heritage Protection Act since 1991. With its streets, canals, and bridges, it forms, together with the neighboring administrative complex, the Kontorhausviertel, a unique example of functionally connected blockhouses that are used differently for offices, warehouses, trade, gastronomy, etc. The overall development comprises 15 large warehouse blocks standing on coniferous piles, built between 1885 and 1927 on 1.1 km long and narrow islands in the Elbe. The complex underwent partial reconstruction between 1949 and 1967. The block buildings were erected in the style of the "Hanoverian School" in red brick and bear witness to an advanced technical development at the time of construction. The neighboring Kontorhausviertel, Europe's first pure office district, was built between the 1920s and 1950s. The Speicherstadt and the Kontorhausviertel with its "flagship" - the Chilehaus - were added to the UNESCO World Heritage List in 2015.

Beginning in the early 1970s, the expansive warehousing located in the Speicherstadt district began to lose its relevance, leading to the arrival of tenants unrelated to the port and a shift in space requirements. The task of renovating and retrofitting these buildings is complex, as it necessitates accommodating the needs of occupants while preserving the buildings' historical authenticity.

Presently, a combination of public and private stakeholders ensures the long-term preservation and sustainability of the property. This involves the preservation of the historic buildings, their distinctive overall impact, and their characteristic presence within the cityscape; enhancing the quality of life for Hamburg's residents by safeguarding this unique testimony to the city's cultural and historical development, which played a key role in shaping its identity; and promoting awareness and disseminating information about the site.

The Research Project and Motivation for the Holistic Neighborhood Approach

Since the recognition of the Speicherstadt in Hamburg as listed buildings and their subsequent inclusion in the UNESCO World Heritage List, their structural transformation not only has to consider the needs of the tenants, the requirements of modern workspaces and fire protection, but also the restrictions of changes to the outer appearance. For these reasons and to meet climate neutrality targets, Hamburger Hafen und Logistic AG (HHLA), the company that develops, designs, and operates the Speicherstadt historical warehouse district, is increasing its efforts to protect the climate, conserve resources and reach CO2-neutrality in the entire complex. To this end, HHLA and a range of partners from the research and scientific community aim to obtain and incorporate renewable energies locally, while maintaining monument compatibility, economic efficiency, and usability.

This is the framework of the 0-CO2-WSHH "CO2-neutrales Welterbe Speicherstadt Hamburg" research project. The project aims to implement modernization and energy efficiency measures to sustainably reduce the CO2 emissions of Speicherstadt's historic district by 2040, addressing, in particular, the key objectives of the German government's "Energy Efficiency Strategy for Buildings". To achieve these goals, the research project is taking a holistic, unique-district approach. This includes a comprehensive consideration of all aspects of buildings' ecological and energy optimization to maximize the use of locally generated renewable energies in the district for heat and power supply.

The project consists of three phases:

- **Phase I. Development and Evaluation**: This phase lays the groundwork for adapting systems and concepts to ensure the sustainable reduction of CO2 emissions while maintaining aspects of compatibility between monuments, economic efficiency, and usability.
- **Phase II. Implementation at Storage Block Level**: In this phase, the measures, components, and concepts tested in Phase I and analyzed through simulation will be selected and tested on Block H under real conditions in a combined form as an example. With the help of monitoring data, the results from the simulations can be comprehensively analyzed and the models validated if necessary.
- **Phase III. Implementation at District Level**: After validation of the implemented measures, HHLA will apply the findings of the holistic approach from the interaction of the Block H measures of the other storage blocks in the entire district.

The project goals and current work described in this paper depict Phase I of the project, which is currently underway.

Work Objectives of the Research Project

The project has five main work objectives, which are presented below.

Record and Analyze Retrofit Measures and Building Properties

First, the **status quo of the retrofitting measures** has to be recorded.

During the building inspections, detailed material-technological, structural, and building-physical features are recorded and analyzed for holistic ecological evaluation.

Furthermore, a digital building model is created in which all relevant building- and neighborhood-related data can be stored to be used by the various simulation and calculation tools with appropriate data interfaces.

Broad-based monitoring is also important. Thus the building system technology in Block H will be designed to ensure that, besides the building automation system, sensors are installed in the four rental units selected for analyzing the indoor air conditions. With these sensors, it is possible to record the indoor air quality, depending on the operation of the ventilation system.

In addition to indoor air conditions and energy consumption for space heating, hot water, and electrical loads, heat flux plates record the dynamic U-values of the building envelope surfaces at selected locations. Sensor systems are also arranged in thermal bridge areas to evaluate condensation failures or the risk of mold growth.

Energy Assessment of the Neighborhood

Another goal is **the analysis and energy assessment of the neighborhood for the energetic upgrading** of the storage block. To systematize the working method for the analysis and assessment of the storage blocks and to obtain the necessary basis for achieving an energy-efficient neighborhood, the tools and methods of the inventory analysis are elaborated and tested in use. By developing a general procedure for holistic energy-efficient and ecological assessment, it should be possible in the future to find suitable renovation concepts for neighborhoods in a simplified way.

Holistic Redevelopment Concept

Another important aspect of the project is the **development of a concept for the holistic redevelopment** of the neighborhood, which considers the historic preservation, energy efficiency, and ecological aspects as well as the physical and structural factors. The goal of a low-CO2 or nearly CO2-neutral energy concept is to significantly reduce CO2 emissions compared to the usual passive house standards. The aim is to undercut these by at least a further 30 percent. The analysis is not limited to the operation of the building but covers the entire life cycle of the building: emissions generated in the course of production, use, and disposal of the refurbishment measures should also be considered. Emissions over the entire life cycle can be calculated using the life cycle assessment method, which is also to be coupled with BIM in addition to the flow simulation models and the thermal building simulation models.

To develop a low-CO2 and ecological neighborhood energy concept, the neighborhood must be mapped with sufficient accuracy using appropriate simulation models in its current structural and plant engineering design. This requires a sufficient level of detail, whereby it must be considered that with an increasing level of detail, the calculation processes become increasingly complex and consequently the requirements for the hardware and software to be used become increasingly demanding. Uncertainties play a significant role in the mapping of such complex models and must not be ignored. The aim here is to record recognized and non-eliminable uncertainties and take them fully into account in the analyses. One challenge is therefore to map the buildings as accurately as necessary and as simply as possible to achieve the best possible informative value.

Innovative Energy Retrofitting Techniques

For this purpose, various renovation measures will be focused on the example of Hamburg's Speicherstadt and tested on Block H. Additionally to elements for generating renewable energy, the energy-related renovation measures also include components that enable the energy generated to be stored locally in the neighborhood over extended periods and used when needed. Components that allow energy transfer at low-temperature levels are also considered.

- On the building envelope, the roof surfaces are suitable for energy retrofitting. Within the scope of the project, optimization potentials concerning system structure, choice of materials, and insulation thickness are investigated to achieve an improvement beyond the usual standard. To this end, **solar energy harvesting roof elements**, compatible with preservation constraints for listed buildings and thermally and electrically activated, are developed. These activated roof elements make it possible not only to generate solar power but also to extract heat from the environment and use it directly in the neighborhood.

  Two roof variants are developed and tested in terms of their energetic effect and technically optimized and adapted in terms of design:

  One variant corresponds to the original appearance of the anthracite-colored roofing of the storage buildings. The small-format roof elements mimic the original slate appearance of the existing roofs. The geometry and color appearance resemble conventional slate shingles but consist of printed glass elements.

Based on a similar principle, another variant has also been developed by printing the glass to resemble copper sheets.

Both variants have already been presented at two trade fairs (in 2022 as well as in 2023) and have received very positive feedback.

- The use of various **heat storage systems** is also being developed and tested in Block H. A thermally activated storage tank made of pile-porous concrete has been developed. Theoretically, about 12 kWh of heat can be stored per cubic meter of thermally activated concrete at a temperature increase of 20 Kelvin. A concrete storage unit of about one cubic meter has been installed in the basement and its potential is being measured in direct use. In addition, the potential of ice storage in direct use is being researched. In this research project, the ice storage system is built on a modular basis, so it is not a permanent facility, but only a temporary one. It can also be expanded or reduced relatively easily.

- The modernization of **ventilation systems** is another relevant parameter in energy retrofitting. Conventional ventilation systems operate with a constant volume flow, which significantly increases the heat demand. This can lead to up to 50 % greater heat energy input compared to classic window ventilation (Intern, 2022). In the project, a variable volume flow control is being tested, where the supply of outdoor air depends on the indoor air condition recorded and evaluated by monitoring. In four selected user units, the demand-oriented operation of the ventilation systems is being tested first simulated and, after installation of a meaningful monitoring concept with variably controllable ventilation systems, during operation under real state conditions in Block H to validate the simulations using CFD (Computational Fluid Dynamics). The findings will be used to consider the use and operation of ventilation systems in the holistic approach.

Inner Courtyard Roofing

Another focus of the project is analyzing the energy-saving potential with an additional roofing of the inner courtyard of Block H.

With a roof, the free exchange of air between the inner courtyard and the outside air is initially prevented. As a result, the temperature conditions in the roofed courtyard will change during the heating period such that the temperatures in the courtyard will rise by a few Kelvin due to the transmission heat losses of the courtyard-side envelope surfaces. Accordingly, the heat losses occurring at the outer walls to the inner courtyard will decrease. The extent to which the roofing contributes to reducing transmission heat losses is being modeled in simplified form with the help of thermal building simulations and analyzed with flow simulations at a higher precision scale. With flow analyses, however, the daily and seasonal ventilation requirements of the inner courtyard must also be calculated; after all, this requires opening wings in the glass roofing that are operated according to demand. Otherwise, the temperatures in the inner courtyard would increase significantly, especially during sunny summer days. Therefore, control scenarios and the determination of the necessary number and areas of openable surfaces are also the subject of the flow analyses.

Again, the BIM model was used as the basis for the simulations. It was also used for the basic architectural studies for the roofing.

Successes Already Achieved in the Current Project

Most of the building surveys have been completed. As a result of the archive inspections, it has been possible to determine which parts of the building are in what original condition (e.g. bomb damage from the Second World War).

The concept for short-term monitoring was also created and the corresponding measurement sensors were installed.

In addition, the exterior and some relevant and accessible areas inside Block H were scanned, thus obtaining point clouds. These were then processed for use in the creation of a BIM expectation model (Fig. 1).

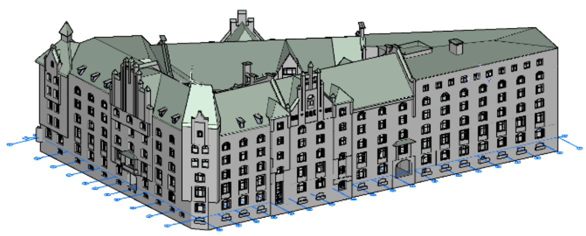

Figure 1: BIM Expectation Model (Source: HCU)

A BIM expectation model is a model created from available information, which is iteratively defined and verified as new geometric and semantic data is received, making it the projects main BIM model

This (main) BIM model is the information centerpiece of the project. It stores the information from the structural analyses and the results from monitoring and short-term measurements. The simulation results from the various simulation programs are also documented here.

For the management of information within the model by the various stakeholders, who do not always have in-depth knowledge of the BIM methodology, a BIM-based dashboard has been developed as a part of the first concept for the use of the BIM model as a database. Thus all relevant project-relevant information can be organized and presented in the BIM model components, acting as information containers. This can be considered a database since the various project, location, materials, spaces, or building elements data can be read and edited. Users can both access and modify the information, including simulation results. This approach to the BIM model as a database not only allows efficient information management but also encourages retrieval, modification, and analysis processes.

In this way, for example, the material data of a wall layer can be retrieved in a bundled form and used for the thermal-hygric simulation which can then save its results into the model too. Similarly, in a floor component, the technical data of the installed underfloor heating can be read out, as well as simulation results of various simulated heating characteristics. In a room, data for the planned use can be stored and simulations for different ventilation and usage behavior can also be found.

Moreover, as the project progressed, the idea of creating a ‘Research Laboratory’ emerged. This is located in part of the ground floor of the building to be analyzed and is intended to serve as a sort of "showcase" for interested parties (Fig. 2).

Figure 2: Floor plan of the ‘Research Laboratory’ (left); Location of the ‘Research Laboratory’ in the building (right) (Source: IWB)

The main aim of the ‘Research Laboratory’ is to test the various retrofitting components and make them visible to the public. Three different interior insulating plasters are analyzed. Moreover, floor, wall, and ceiling heating systems were installed. The heating systems in walls and ceilings are a carbon paint heating system and an electric textile heating panel. This allows the testing of different heating options. Ventilation systems were also installed at the four main windows. This allows different ventilation behaviors to be simulated. The measurement results from the different test series of the ventilation scenarios are used to validate the flow simulations using StarCCM+ and the different tests of the utilization scenarios of the dynamic building simulation.

Apart from the investigations at room level, the retrofitting components for the overall system have already been implemented on the systems engineering side. The hybrid roof elements were developed in both copper sheet and slate roof optics and installed on a test roof area.

Figure 3 shows the hybrid roof elements with a copper look. The current design imitates sheet copper in its non-oxidized form. The copper look can also be developed as a copper sheet with a patina.

Figure 3: Copper-look roof element (Source: Eckpack GmbH)

Figure 4 shows hybrid roof elements with a slate look. Three different looks of slate imitation were developed and applied to the test roof surfaces. Each of them is clad with real slate.

Figure 4: Slate-look roof element (Source: Eckpack GmbH)

An ice storage tank and a solid matter storage tank were also installed in the basement of the property in question. The interaction of the components in combination with a heat pump is to be tested in different control scenarios using the installed measurement sensors.

Figure 5 schematically shows the interaction of the various retrofitting components.

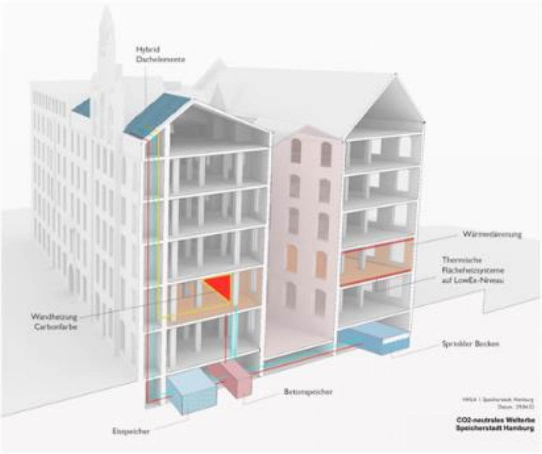

Figure 5: Schematic representation of the individual components in the test object (Source: Demirag Architekten)

The idea of a (semi) transparent roof over the inner courtyard is being investigated in the project. Initially, it was considered a purely theoretical possibility. The following qualitative findings were obtained from initial rough simulations. Roofing over the inner courtyard reduces the building's heating energy requirement. The higher the roofing of the inner courtyard is installed; the more heating energy can be saved in the building as a whole. The installation of doors or similar in the three passages to the inner courtyard has a major influence on the heating energy savings. The energy quality (U-value) of the material of the roofing and the passageways only plays a small part in reducing the building's heating energy. A reduction in heating energy simultaneously leads to a (theoretical) increase in the building's cooling energy. To avoid this increase, a system must be developed to ventilate the inner courtyard in the summer months, either through targeted leaks in the structures or by automatically opening the access doors.

Associated Research Questions and Methodological Approaches

Several research questions arise from the research project. The most obvious is probably the question of which measures in combination with which energy concepts in conjunction with neighborhood networking will reduce CO2 emissions in the Speicherstadt to make it CO2-neutral in the long term. Another question is certainly how to optimize the networking. This is followed by the further question of how CO2 neutrality can be achieved not only in operation but also from a holistic point of view and, above all, how the optimization of the retrofit concepts can work from a holistic perspective.

The innovative approach of using a BIM model as a central source of information exchange in the historic building stock raises further questions:

How can a Building Information Model (BIM) be developed and applied to enable comprehensive simulation and analysis processes, with a particular focus on information management for the operation of buildings and neighborhoods? Where does the inadequate use of BIM models for operational aspects such as energy saving and resource efficiency come from? How can the project presented here contribute to filling these gaps? These questions can in turn be answered with further "detailed" ones. As long as these are not clarified, the above questions will answer themselves in the negative. The following questions need to be clarified in detail: How can user groups without authoring programs modify and add semantic data to BIM models? How are they verified and approved? Are properties and property sets implemented in the BIM model correctly read into the simulation software? And how can new parameters be inserted?

The holistic energy and ecological assessment approach also raises further research questions. The most important one is probably how exactly this approach can be used to assess and even optimize retrofit options since both energy and ecological assessment are often based on uncertainties and assumptions. These lead directly to an interval-based assessment, whereby the range of results can already be estimated, or to a difference between calculation or simulation results and measurements. However, coupling both assessments (energy and ecological) is essential for a holistic assessment.

Conclusion

The project ranges from theoretical basic research to application-oriented development issues, which is made possible by the heterogeneous consortium of university, company, and client. It thus offers the opportunity to directly test research and development results from science and companies regarding their practical suitability on a real block of the listed Speicherstadt Hamburg district. At the same time, this approach poses several challenges.

Many individual objectives were delayed due to supply bottlenecks and an omnipresent shortage of skilled labor (including the university environment). As a result, not all events could be performed in the planned sequence and new workflows also had to be developed. Nevertheless, much has already been achieved in the project, as this report shows. The subsequent monitoring phases and their evaluation will show whether CO2 neutrality can be achieved not only in theory but also in practice in historical monuments.

Acknowledgments

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The research project is structured as a joint project and includes the following partners: HHLA 1. Speicherstadt Immobilien GmbH & Co. KG as the joint coordinator, the Institut für Wekstoffe im Bauwesen at Universität Stuttgart, the BIMLab at HafenCity Universität Hamburg, and the Lehrstuhl für Gebäude- und Raumklimatechnik at RWTH Aachen. In addition, the Behörde für Umwelt, Klima, Energie und Agrarwirtschaft, and the Behörde für Kultur und Medien with the Denkmalschutzamt der Freien und Hansestadt Hamburg are involved as associated partners.

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