Final report

Digitalization framework for energy optimization and smart maintenance of historic buildings

Shaofang Gong, Linköping University

Project number: 50043-1

FÖRORD

Spara och bevara är ett forsknings- och utvecklingsprogram som Energimyndigheten initierat för att öka kunskapen om energieffektivisering i kulturhistoriskt värdefulla byggnader. Programmet syftar till att utveckla och förmedla kunskap och tekniklösningar som bidrar till en energieffektivisering i dessa byggnader utan att deras värden och inventarier förstörs eller förvanskas.

Den varsamma energieffektiviseringen ska uppnås genom interdisciplinära samarbeten, där teknik möter kulturvård. Målet är att skapa en bestående kunskapsgrund inom området energieffektivisering i kulturhistoriskt värdefulla byggnader och bidra till en långsiktig, hållbar förvaltning av det äldre fastighetsbeståndet.

Programmet samordnas av Uppsala universitet.

Rapporten redovisar projektets resultat och slutsatser. Publicering innebär inte att Energimyndigheten eller Uppsala universitet tar ställning till framförda slutsatser, resultat eller eventuella åsikter.

Sammanfattning

Med finansiering (2020-2024) från Energimyndigheten för projektet ”Digitaliseringsramverk för energieffektivisering och smart underhåll av historiska byggnader”, har Linköpings universitet, Campus Norrköping tillsammans med samarbetspartners Uppsala universitet, Campus Gotland, RISE Research Institutes of Sweden i Linköping och Norrevo Fastigheter AB i Norrköping tagit fram en helhetslösning för digitalisering av historiska byggnader. Det är en ”one-stop service”-lösning, det vill säga en hel lösning med all nödvändig hårdvara och mjukvara i ett paket tillhandahålls användare som vill delta i en digitaliseringsprocess, gällande inomhusklimat, energieffektivitet och optimalt bevarande av historiska byggnader. En användare får till exempel en molnlänkad Edge-enhet och ansluter den till ett 230-V-uttag på en vald plats, och sedan skickas mätdata trådlöst till molnet, lagras automatiskt och visualiseras omedelbart på den utvecklade Minerva-plattformen. Efter databehandling med en vald maskininlärningsalgoritm i molnet skapas smarta applikationer, till exempel via applikationsprogrammeringsgränssnittet. De lagrade data kan även exporteras till tredje part för deras egna applikationer. En doktorand som arbetar för projektet tog sin licentiatexamen i oktober 2023 och har planerat att försvara sin doktorsavhandling i mars 2025. Dessutom har två avslutade doktorsavhandlingar, den ena vid Linköpings universitet och den andra vid Uppsala universitet, delvis finansierats av projektet. Projektet har hittills resulterat i sex tidskriftsartiklar, fem konferensartiklar och två populärvetenskapliga artiklar, medan ytterligare två manuskript är under bearbetning för publicering i tidskrifter.

Två huvudsakliga fallstudier har genomförts av Uppsala universitet. Den första studien avser de antikvariska aspekterna som bör beaktas i relation till utvecklingen av ett digitaliseringsramverk för energioptimering och smart underhåll av tre historiska byggnader inom Norrköpings kommunala fastighetsbolag Norrevos fastighetsportfölj. Den andra studien avser de antikvariska aspekterna som bör beaktas vid utvecklingen av ett digitalt optimerat system för inomhusklimat i historiska byggnader med samlingar in situ, t.ex. Löfstad slott i Östergötland. Detaljer om dessa studier finns i en av de bifogade bilagorna.

Huvudresultaten från RISE:s verksamhet har visat följande. 1) Det var viktigt att balansera datareduktion och noggrannhet för att säkerställa effektiv rensning av Edge-data. 2) CNN (Convolutional Neural Network)-modellen för att uppskatta strömförbrukningen visade sig vara en adekvat indikator på energiförbrukningen. Trots detta bör transformatormodeller inte kasseras eftersom de har visat potential i andra implementeringar. 3) Ändringsdetektering, som ofta används i smarta klockor för att gissa när en person går, springer eller cyklar, skulle kunna användas med en artificiell intelligens-modell för att övervaka och varna för drastiska förändringar i inomhusklimatet eller när mätningar överskrider vissa trösklar. Detaljer om dessa studier finns i en av de bifogade bilagorna

Nyckelord: Digitaliseringsramverk, Digitala tvillingar, Historiska byggnader, Artificiell intelligens, Energieffektivisering, Förvaltning, Brukande, Bevarande

Summary

With funding (2020-2024) from the Swedish Energy Agency (Energimyndigheten) for the project "Digitalization framework for energy efficiency and smart maintenance of historic buildings", Linköping University, Campus Norrköping together with cooperation partners Uppsala University, Campus Gotland, RISE Research Institutes of Sweden in Linköping and Norrevo Fastigheter AB in Norrköping have developed a holistic solution for digitalization of historic buildings. It is a one-stop service solution, i.e., an entire solution with all needed hardware and software in a package is provided to users who wish to participate in a digitalization process, concerning indoor climate, energy efficiency and optimal conservation of historic buildings. For instance, a user gets a Cloud-linked Edge device and plug it to a 230-V outlet at a chosen place, and then measurement data are wirelessly sent to the Cloud, automatically stored, and instantly visualized on the developed Minerva platform. After data processing with a chosen machine learning algorithm in the Cloud, smart applications are created, e.g., via the application programing interface. The stored data can also be exported to third parties for their own applications. A Ph.D. student working for the project received his Licentiate degree in October 2023 and has planned to defend his Ph.D. thesis in March 2025. In addition, two finished Ph.D. dissertations, one at Linköping University and the other at Uppsala University, have been partially funded by the project. The project has so far resulted in six journal papers, five conference papers and two popular science articles, while another two manuscripts are under processing for publication in journals.

Two main case studies have been carried out by Uppsala University. The first study concerns the antiquarian aspects that should be considered in relation to the development of a digitization framework for energy optimization and smart maintenance of three historic buildings in Norrköping managed by the municipal company Norrevo Fastigheter AB. The second study concerns the antiquarian aspects that should be considered in the development of a digitally optimized system for indoor climate in historic buildings with in situ data collections, e.g. the Löfstad Castle in Östergötland. Details of these studies can be found in one of the attached appendixes.

RISE has focused on surveying existing AI solutions for both heritage preservation and energy saving as well as implementing and testing methods for data reduction, a convolutional neural network (CNN) and change detection in digital twins. Main findings from RISE's activities have shown the following. 1) It was important to balance data reduction and accuracy to ensure efficient edge data cleaning. 2) The CNN model for estimating power consumption proved to be an adequate indicator of energy consumption. Despite this, transformer models should not be discarded as they have shown potential in other implementations. 3) Change detection, often used in smart watches to guess when a person is walking, running, or biking, could be used with an artificial intelligence model to monitor and warn of drastic changes in indoor climate or when measurements exceed certain thresholds.

Keywords: Digitalization Framework, Digital Twins, Historical Buildings, Artificial Intelligence, Energy Efficiency, Energy Management, Energy Use, Building Conservation

Content list

1. Introduction and background

This project was financed by the Swedish Energy Agency (Energimyndigheten) from 2020 to 2024. Linköping University (LiU) is the coordinator, and partners are Uppsala University (UU), RISE Research Institutes of Sweden (RISE) and Norrevo Fastigheter AB (Norrevo). Main results of the project have been presented in this final project report of LiU as the project coordinator. Moreover, final reports concerning more details related to activities and findings at UU and RISE are attached as two appendixes.

1.1 Background

New technologies like Internet of Things (IoT) and artificial intelligence (AI) for digitalization purposes have a long-term goal to collect, analyze and utilize data as well as to create AI based on those data. In the cultural heritage and historic building areas, there exist widespread needs for digital transformation but lack of good solutions. For instance, to create a virtual space of a historical building, i.e., a digital twin, is very useful for smart maintenance of the building against the impact of climate change and for energy efficiency. However, except some efforts to create three dimensional (3D) models of some buildings, few truly functional digital twins of historical buildings exist either in Sweden or in other EU countries according to our published previous study [1]. One major reason why few real-world solutions exist is that it is a multidisciplinary challenge requiring through integration of domain specific knowledge and digitalization techniques.

With funding from Energimyndigheten from 2020 to 2024, Linköping University, Campus Norrköping (LiU Norrköping) together with cooperation partners Uppsala University, Campus Gotland (UU Gotland), RISE Research Institutes of Sweden in Linköping (RISE Linköping) and Norrevo Fastigheter AB in Norrköping (Norrevo) have developed a holistic solution named Minerva [2] for digitalization of historic buildings. Minerva is a kind of Digitalization Service as a Solution (DSaaS), consisting of own-developed Edge hardware and software with multiple sensors linked to Cloud, for data acquisition, communication, cleaning, storage, analysis, visualization, and utilization. Minerva aiming at fully automated digitalization services provides a unique solution for digitalization of historic buildings within the Spara & Bevara program [3]. Minerva has reached the Technology Readiness Level 5 (TRL 5), since it has been under validating with various kinds of stakeholders such as Löfstad Castle [4] in Östergötland, Riddarhuset [5] in Stockholm, Stångåstaden [6] in Linköping, the City Theater, the City Museum and the Auditorium in Norrköping, as well as several cases managed by Akademiska Hus. UU Gotland has also several cases set up together with Nordic Museum (Julita manor) in Sörmland and with Kungliga Vitterhetsakademien (Stjernsunds castle) in Närke, etc. All these cases can be seen at the Minerva website under Dashboard [2].

1.2 Goal and objectives

The ultimate research goal is a Cloud-based digitalization solution with both IoT and AI capacities for maintaining unique characters that define values of historic buildings while saving energy. Main objectives to reach the project goal are the following:
1) Data collection and communication: to utilize proper sensors and wireless communication protocols for creating data concerning historic buildings, indoor environment and outdoor climate.

2) Data storage and processing: the created data are stored in a database within, e.g., Microsoft Azure Cloud, so that data processing can be done in the Cloud.
3) Digital twins: Digital models as virtual buildings are created based on real-time and historical data stored in the Cloud. AI is developed for smart building maintenance and energy saving purposes.
4) Field tests of energy efficiency with digital twins in chosen historic buildings. This is done in collaboration with associated partners, e.g., Norrevo and Löfstad Castle.
5) The developed digitalization framework with digital twins can be transported as a digital container to different stakeholders, e.g., for academic study or for possible future commercialization, either in Sweden or abroad.

1.3 Coverage and limit

The project is aimed at a Cloud-based digitalization framework for energy optimization with smart maintenance of historic buildings. Digital twins corresponding to chosen historic buildings are created and stored in the Cloud. AI is developed into the digital twins. These techniques provide a further understanding of the operating conditions of historic buildings. For example, it will be possible to control heating depending on the existing and expected number of people in a building. By linking this information to expected heating costs at a given time, it is possible to optimize the cost of heating to a high level. Especially, considering global climate change, Cloud-based services with AI provide new opportunities in terms of climate-adaptive energy optimization in historic buildings. This is a cross-disciplinary project that requires multiple competences, but it is limited to the area of digitalization of historic buildings.

2. Activity

The project has been planned and accordingly carried out with the following four work packages (WP1-WP4) including the specified tasks. All the listed deliverables are available upon request.

WP1: Specification, dissemination and commercialization (LiU Norrköping, UU Gotland, RISE Linköping and Norrevo)
Task 1.1. Survey of global digitalization trend with IoT and cloud (LiU Norrköping)
Deliverable: Written report.
Task 1.2. Need for improved tools for maintenance of historic buildings (UU Gotland)
Deliverable: Written report.
Task 1.3. AI solutions for both heritage preservation and energy saving (RISE Linköping)
Deliverable: Written report.
Task 1.4. Investigation of critical points for collection of data (Norrevo)
Deliverable: Written specification.
Task 1.5. Dissemination of scientific results (LiU Norrköping and UU Gotland)
Deliverable: High quality journal and conference papers.
Task 1.6. Commercialization of project results (Norrevo and RISE Linköping)
Deliverable: Summary of application cases both within and outside the project.

WP2: Data creation and communication (LiU Norrköping, UU Gotland and Norrevo)

Task 2.1. Study and verification of sensors including digital cameras to be used (LiU Norrköping and UU Gotland)
Deliverable: Written report of test and verification results.
Task 2.2. Study and verification of wireless communication protocols to be used (LiU Norrköping and Norrevo)
Deliverable: Written report of test and verification results.
Task 2.3. Prototyping of sensor fusion with multiple sensors (LiU Norrköping and UU Gotland)
Deliverable: Finished design and prototypes of a multiple sensor station.
Task 2.4 Demonstration of data communication to cloud (LiU Norrköping, UU Gotland and Norrevo)
Deliverable: A workshop about cloud-based data communications within "Spara och Bevara".

WP3: Data storage and processing (LiU Norrköping and RISE Linköping)
Task 3.1. Database creation in cloud, e.g., Microsoft Azure Cloud (LiU Norrköping and RISE Linköping)
Deliverable: A structured database in Cloud for creations of digital twins of cultural and historical buildings.
Task 3.2. Data cleaning with an edge device (RISE Linköping and LiU Norrköping)
Deliverable: Linux-based local gateway/edge device for reducing data amount to the cloud.
Task 3.3. Data storage in an SQL database (LiU Norrköping and RISE Linköping)
Deliverable: Structured data storage for digital twins in an SQL database.
Task 3.4. Data analytics and machine learning (RISE Linköping and LiU Norrköping)
Deliverable: Methods for data analytics and machine learning both in Linux-based gateway/edge device and in Cloud.

WP4: Study of heritage preservation and energy saving with digital twins and AI (LiU Norrköping, UU Gotland, RISE Linköping, and Norrevo)
Task 4.1. Creation of digital twins in Cloud, e.g., Microsoft Azure Cloud (LiU Norrköping and Norrevo)
Deliverable: Demonstration of functional digital twins.
Task 4.2. Artificial intelligence for digital twins (RISE Linköping and LiU Norrköping)
Deliverable: Demonstration of AI for cultural and historical buildings.
Task 4.3. Field study at Stadsteatern, Hörsalen and Stadsmuseet in Norrköping. (UU Gotland, LiU Norrköping, and Norrevo)
Deliverable: Scientific papers for open access journals or conferences
Task 4.4. Study of energy saving with digital twins (LiU Norrköping and UU Gotland)
Deliverable: Scientific papers for open access journals or conferences

3. Results

As a one-stop service solution, the developed DSaaS-platform named Minerva with all needed hardware and software in a package is provided to users who wish to participate in a digitalization process, concerning indoor climate monitoring, energy efficiency and optimal conservation of historic buildings. It is a plug-and-play service as seen by users. For instance, a user gets a Cloud linked Edge device and plug it to a 230-V power outlet at a chosen place, and then measurement data are wirelessly sent to the Cloud, automatically stored, and instantly visualized on the DSaaS platform. After data processing with a chosen machine learning (ML) algorithm in the Cloud, smart applications are created, e.g., via the application programing interface (API). The stored data can also be exported to third parties for their own applications. One special case has been with the Löfstad Castle that is managed by Östergötland Museum. Twelve smart sensor boxes with total 78 sensors have been installed and a digital twin has been created with continuously collected data, aiming at reducing energy use of the castle, while preserving this monumental culture heritage.

Case studies reported by UU Gotland have shown that the developed DSaaS platform Minerva made it possible for users to quickly access data from the digital collection/monitoring of the indoor climate in a clear way. Knowledge of how the buildings function and perform can, by extension, contribute to knowledge about the buildings and management that leads to increased energy efficiency and a more optimal climate for interiors and collections in the buildings that were included in the studies. The technical results that have been compiled by LiU Norrköping and RISE Linköping respond to the main purpose of the project, while the study that highlights the antiquarian aspects shows needs and opportunities from a user perspective as well as a conservation perspective. There are concerns that technical systems should also be able to be handled manually on certain occasions. But it is also about the fact that manual handling needs routines which in turn are followed up and checked. Knowledge is highlighted as an important aspect to be able to manage buildings with cultural values in the most sustainable way possible. In this case, sustainability is about not only increased energy efficiency and reduced climate footprint, but also sustainable preservation and management of the buildings' cultural values together with the interiors and collections that the buildings contain. Knowledge that there is a need to strengthen includes both technical knowledge and understanding of how the buildings and their indoor climate work and what can be done to achieve as optimal an indoor climate as possible for each building's needs.

Main findings from RISE's activities are the following: 1) The initial data reduction approach implemented with the edge device involved simple removal of samples, reducing the data sampled at 1Hz to a measurement every 10 seconds. This had minimal impact on the verification score, but further reduction without re-training the CNN (Convolutional Neural Network) model lowered the accuracy. The other method used was a statistics vector containing mean, max, min, and standard deviation, which provided significant information but wasn't fully utilized by the existing AI/ML model. This highlights the importance of balancing data reduction and accuracy to ensure efficient edge cleaning. 2) The CNN model for estimating power consumption proved to be an adequate indicator of energy consumption. Comparisons with a transformer model showed that the CNN was more effective. This was likely because energy consumption doesn't fluctuate much daily, making the CNN model more suitable for short-term predictions. Despite this, transformer models should not be discarded as they have shown potential in other implementations. 3) Change detection is often used in smart watches to guess when a person is walking, running, or biking. The idea was to use an AI-model to monitor and warn of drastic changes in indoor climate or when measurements exceed certain thresholds. Although promising, there was not enough time to test this idea properly, especially since it required annotated data does not exist. This area holds potential for future work, emphasizing the need for accurate change detection in AI digital twins to enhance monitoring and predictive capabilities.

4. How to utilize the results

The main result from the project is a one-stop DSaaS solution, i.e., an entire solution with all needed hardware and software in a package is provided to users who wish to participate in a digitalization process, concerning indoor climate, energy efficiency and optimal conservation of historic buildings. The DSaaS solution encompasses all aspects concerning digitalization, including data acquisition, communication, cleaning, storage, analysis, visualization, and utilization, providing end users with comprehensive digitalization services. The simplicity and accessibility of the solution, along with its low cost, make it an attractive option for owners and managers of historic buildings who may lack digitalization knowledge and resources. With a more flexible maintenance, the DSaaS solution also eases public access to the cultural historic buildings, providing more educational value to the society.

Examples for applications are described in detail in the final report of Uppsala University (see the attached file in the Appendix) as well as in the final report of RISE (see the attached file in the Appendix). These applications include three historic buildings in Norrköping, i.e., the City Theater, the Auditorium and the City Museum. Moreover, case studies for applications in other historic buildings have also been done, including the Löfstad Castle in Östergötland, the Stjernsund Manor in Närke and the Julita Manor in Sörmland, etc.

From the future research point of view, further activities (A1-A3 as described below) with new projects can be done together with new application partners.
A1: Further technology development based on the DSaaS platform Minerva, including enhanced security measures.
A2: Enhancing societal resilience with the DSaaS platform concerning heritage conservation against climate change and other threats.
A3: On-site demonstration and result spreading for real-world applications of the DSaaS solution together with application partners.

More details of the above three new activities (A1-A3) are described below.
A1: Technology development of a complete DSaaS solution with high security. The DSaaS solution will enable better preparedness, timely responses, and smart decision-making to minimize damage and enhance resilience of historic buildings. A focus will be on Edge-Cloud collaboration to enhance security and safety with new concepts like Federated Learning such that sensitive user data are only saved locally in Edge devices (not sent to Cloud), while smart functions are generated with co-training of AI models in both Edge and Cloud (our developed Edge device enables this kind of Federated Learning with Edge-Cloud collaboration). The new outcomes of the project will enable enhanced data security and risk minimization, while fully utilizing the benefits of smart DSaaS applications in the society.

A2: Measures for heritage conservation against climate change and other threats. Measures for mitigating the damage processes and for long-term preservation, as well as integration of risk assessment tools in the interface of the digital twin. A digitalized method for long-term conservation of a historic building like the Löfstad Castle with respect to both indoor and outdoor climates. The digitalized conservation method can also be used by many other historic buildings, in Sweden and possibly in other EU countries.

A3: Demonstration for real-world applications. DSaaS is showcased at historic buildings like the Löfstad Castle and used by other stakeholders, having the potential for widespread applications or possible commercialization in the future. The outcome of the project contributes to UN Agenda 2030 Goal 11.4: Strengthen efforts to protect and safeguard the world's cultural and natural heritages.

Last but not least, the EU Commission has recently (august 2024) approved a new cooperation project (2024-2027) named “Optimizing Positive-Energy Districts through Interoperable Digital Platforms (OPTIX)” within the program Clean Energy Transition Partnerships, in which the developed Minerva framework will be utilized. As illustrated by the block diagram below (Fig. 1 OPTIX framework overview in the project proposal), the Minerva framework is one of the key platforms to be utilized for Digitalization for Energy Systems. The project is coordinated by the Technical University of Danmark, having totally 12 partners from multiple EU countries.

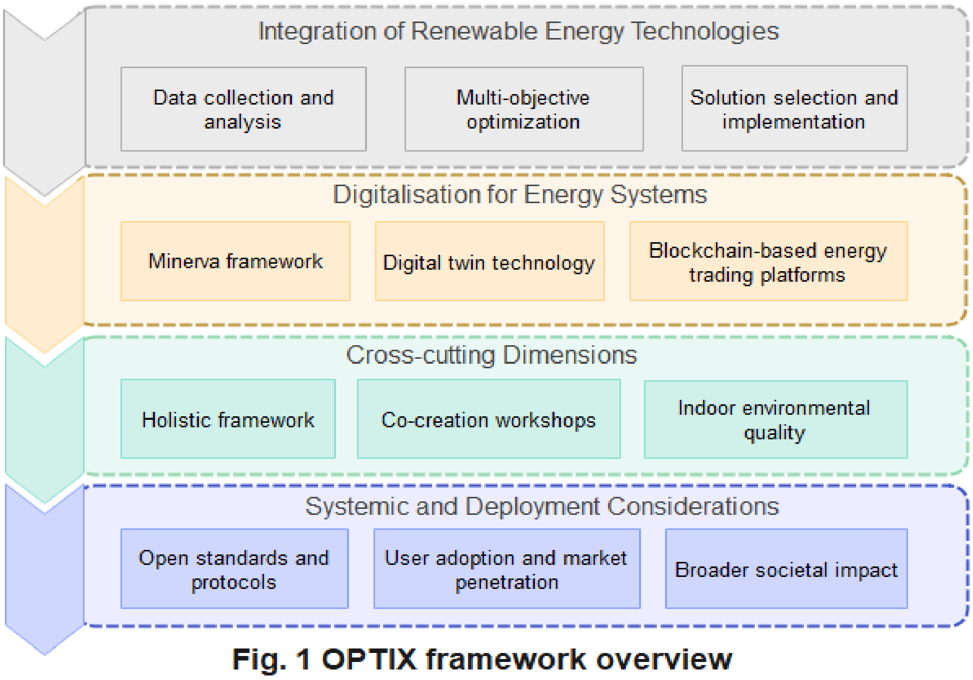

Fig. 1 OPTIX framework overview

5. Discussion

As an application example, unlike other digitalization solutions that create digital twins of 3D models, Minerva creates so-called parametric digital twins for transformation from a physical space to a virtual space, creating digital functions with continuously monitoring data from different and multiple sensors. For instance, smart maintenance of buildings can be done with a chosen machine learning/deep learning model based on a complete set of environmental data. Advantages with the Minerva digitalization solution are listed below. Minerva has so far reached the Technology Readiness Level 5 (TRL 5), since it has been under validating with different kinds of stakeholders. However, more study and development are needed to reach TRL 8 or 9 for widespread applications or possible commercialization in the future. As demonstrated by the approved OPTIX proposal above, innovative projects with new fundings can be created based on the developed Minerva framework. The advantages and potentials associated with Minerva are listed below.

1) It is a holistic digitalization service solution, i.e., Digitalization Service as a Solution, but not Digitalization Solution as a Service, with all needed hardware and embedded software for data acquisition, communication, cleaning, storage, analysis, visualization, and utilization. A user only needs to plug a smart device into a power outlet at a chosen location.
2) Low cost to end users since they can just rent a service from the Minerva manager under a certain period or in long term. It provides a cost-effective alternative by offering an easily scalable subscription-based service, allowing owners and managers to rent the necessary hardware with embedded software for their digitalization needs, reducing upfront costs and making it more accessible for a wide range of buildings.
3) Local Edge server with IoT and AI capacities for decentralized, i.e., distributed deployments in a building, a multi-building area, a town, or a city.
4) It is secure for the Minerva manager to maintain the digitalization system with a proven Cloud service provider like Microsoft Azure Cloud.
5) Distributed AI can be provided to end users, since the Edge servers with multiple sensors/actuators are wirelessly linked to Cloud.
6) The Smart Sensor Box prototype, consisting of an Edge server with different sensors/actuators wirelessly linked to Cloud, has been manufactured in the Electronics Lab of LiU, and provided to Minerva partners today. Mature products can surely be manufactured in Sweden in the future.
7) Since Minerva will provide one-stop digitalization services to stakeholders or end users (not to provide only products or consulting services), it will always be an open platform flexible for research and development.
8) With the added values listed above, it is estimated that the ratio of price to cost for providing DSaaS is between 300-400%.

According to case studies done by UU Gotland, a transparent and accessible system for the collection, display and follow-up of data relating to the indoor climate and energy consumption is necessary to identify opportunities for energy saving. Such a system also involves learning about the buildings from the functions and people who are tasked with managing, looking after and maintaining the buildings. The information that the users were able to access via the Minerva platform has filled such a need. There is also support in the sub-studies that data concerning not only the indoor climate but also information about how the buildings are used would be valuable for smart control of the indoor climate.

RISE has reported that in the Big Data era, data-driven models rely on statistical algorithms to capture possible correlations in a dataset. The most sophisticated of these models are known as ML and AI models. The dataset consists of multiple measurements capturing the actual state of the building at different times obtained from multiple sensors. The sensors collecting the data can be installed when the building has been built or afterwards. With the proliferation of IoT technologies such datasets are getting more and more easy to obtain. And the electronic devices that are used for collecting the physical measurements are inexpensive. Nowadays, several well-developed open-source software libraries are available for implementing such ML/AI models. However, data-driven models are very sensitive to the quality of the dataset in terms of completeness and correctness. Very important for a good and robust AI-model is that it covers most, if not all, possible combinations of states the system can be in and that those states are well represented in the dataset. So, in the case of buildings, the collection of a good and balanced dataset will take a few years. The reason for that is that one need to collect data from all seasons and different weather conditions.

6. Conclusion

A holistic solution named Minerva for digitalization service of historic buildings has been successfully studied and developed, consisting of customer-developed Edge hardware and software with multiple sensors/actuators linked directly to Cloud, for data acquisition, communication, cleaning, storage, analysis, visualization, and utilization. The unique concept of Digitalization Service as a Solution associated with the Minerva digitalization framework is interesting not only for historic buildings, but also for other smart digitalization purposes, which has been demonstrated not only with pilot applications in Sweden but also with a recently approved EU cooperation project entitled "Optimizing Positive-Energy Districts through Interoperable Digital Platforms (OPTIX)" in which Minerva is one of the key platforms that will be utilized for digitalization of energy systems within districts in cities of EU countries.

Case studies done by UU Gotland have identified a number of development areas concerning digitalization of historic buildings. These areas include knowhow, communication, tailored technical systems, long-term contingency preparedness and sustainable management of historic buildings, which are central to the work of managing and conserving these buildings in the safest possible way. These areas could usefully be elaborated and form the basis of guidelines or even a standard. Considering that a standard should respond to common solutions to recurring problems and create unified and transparent methods and models for finding solutions to solve the problems. However, today there is a lack of guidelines and standards that focus on the management and maintenance processes for buildings with cultural values.

Main findings from RISE's activities have shown the following. 1) It was important to balance data reduction and accuracy to ensure efficient edge data cleaning. 2) The CNN model for estimating power consumption proved to be an adequate indicator of energy consumption. Despite this, transformer models should not be discarded as they have shown to have potential in other similar implementations. 3) Change detection, often used in smart watches to guess when a person is walking, running, or biking, could be used with an AI-model to monitor and warn of drastic changes in indoor climate or when measurements exceed certain thresholds.

7. Publication list

Publications with results from the project in both peer reviewed journals and international conferences as well as in popular science are listed below.

A. Articles in Peer-reviewed Journals

1) Hupkes Jelrik, Leijonhufvud Gustaf, Ni Zhongjun, Eriksson Petra, Gong Shaofang, “Challenges in indoor climate control for energy optimisation in Swedish manor houses”, draft paper for scientific publication, 2024.

2) Z. Ni, C. Zhang, M. Karlsson, and S. Gong, “A study of deep learning-based multi-horizon building energy forecasting,” Energy and Buildings, vol. 303, 2024.

3) Z. Ni, Y. Liu, M. Karlsson, and S. Gong, “Enabling Preventive Conservation of Historic Buildings Through Cloud-based Digital Twins: A Case Study in the City Theatre, Norrköping,” IEEE Access, vol. 10, pp. 90924-90939, 2022.

4) Y. Liu, S. Mousavi, Z. Pang, Z. Ni, M. Karlsson, and S. Gong, “Plant Factory: A New Playground of Industrial Communication and Computing,” Sensors (Basel), vol. 22, no. 1, p. 147, 2022.

5) Y. Liu, Z. Ni, M. Karlsson, and S. Gong, “Methodology for digital transformation with Internet of Things and cloud computing: A practical guideline for innovation in small- and medium-sized enterprises,” Sensors (Basel), vol. 21, no. 16, p. 5355, 2021.

6) Z. Ni, Y. Liu, M. Karlsson, and S. Gong, “A sensing system based on public cloud to monitor indoor environment of historic buildings,” Sensors (Basel), vol. 21, no. 16, p. 5266, 2021.

B. Articles in Peer-reviewed Conference Proceedings

1) Hupkes Jelrik, Leijonhufvud Gustaf, Ni Zhongjun, Eriksson Petra, Gong Shaofang, “Digitalisation framework for energy optimisation and smart maintenance of historic buildings: Development and implementation at Löfstad manor, Sweden”, abstract sent to EEHB2024.

2) Z. Ni, C. Zhang, M. Karlsson, and S. Gong, “Edge-based Parametric Digital Twins for Intelligent Building Indoor Climate Modeling,” in the 20th IEEE International Conference on Factory Communication Systems, Toulouse, France, Apr. 17-19 2024.

3) Z. Ni, C. Zhang, M. Karlsson, and S. Gong, “Leveraging Deep Learning and Digital Twins to Improve Energy Performance of Buildings,” in the 3rd IEEE International Conference on Industrial Electronics for Sustainable Energy Systems, Shanghai, China, Jul. 26-28 2023.

4) Z. Ni, Y. Liu, M. Karlsson, and S. Gong, “Link historic buildings to cloud with Internet of Things and digital twins,” in the 4th International Conference on Energy Efficiency in Historic Buildings, Benediktbeuern, Germany, May 4-5 2022.

5) Z. Ni, P. Eriksson, Y. Liu, M. Karlsson, and S. Gong, “Improving energy efficiency while preserving historic buildings with digital twins and artificial intelligence,” in SBE21 Sustainable Built Heritage, Via Volta, Bolzano, Italy, Apr. 14-16, 2021.

C. Popular Science Articles

1) Donarelli Anna, "Applying advanced digital technology for indoor climate control in historic buildings – a case study of user perspectives and needs", project report, 2023 (available upon request), Uppsala University.

2) Zhongjun Ni, Yu Liu, Magnus Karlsson och Shaofang Gong, "Mångsidig sensorlåda för smarta digitaliserings- tillämpningar", *Elektroniktidningen*, 17 maj 2021

8. References

[1] https://ieeexplore.ieee.org/abstract/document/9868776

[2] https://historicbuildings.azurewebsites.net

[3] https://sparaochbevara.se/

[4] https://lofstad.se/

[5] https://www.riddarhuset.se/

[6] https://www.stangastaden.se/

9. Appendixes

- Final project presentation at the ending conference of the "Spara och bevara" program in Visby, March 20-21, 2024 (Final report-presentation.pdf).
- Final report from UU Gotland (Appendix-UU report.pdf).
- Final report from RISE Linköping (Appendix-RISE report.pdf).
- Z. Ni, A Digitalization Framework for Smart Maintenance of Historic Buildings, Licentiate thesis, DOI: 10.3384/9789180753050

https://liu.diva-portal.org/smash/record.jsf?pid=diva2%3A1793044&dswid=273