TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

IMPLEMENTATION OF IOT CONCEPT FOR LIFE CYCLE ASSESSMENT OF MODULAR WOODEN HOUSES: A WAY TO ACHIEVE A CIRCULAR ECONOMY

IOT-KONTSEPTI RAKENDAMINE PUIT MOODULMAJADE ELUTSÜKLI HINDAMISEL: VIIS RINGMAJANDUSE SAAVUTAMISEKS

MASTER THESIS

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Tallinn 2022

(*On the reverse side of title page*)

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THESIS TASK

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Thesis topic:

Implementation of IoT Concept for life Cycle Assessment of modular wooden houses: a way to achieve a circular economy.

IoT kontsepti rakendamine puit moodulmajade elutsükli hindamisel: viis ringmajanduse saavutamiseks.

Thesis main objectives:

- To study and understand the concepts: LCA (Life Cycle Assessment) of wooden houses, the role of IoT for data acquisition and monitoring, CE (Circular Economy) driven by IoT
- To develop a conceptual model for LCA of rental modular wooden houses based on IoT product tracking
- To analyze and monitor the life cycle process of rental modular wooden houses and suggest control mechanism for improvement of data that leads to declaring product recycling stages and data quality in calculations

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Study and define the concepts of Life-cycle of wooden modular houses, and CE driven through IoT	14/11/2022
2.	To develop a conceptual model for LCA of Rental Modular wooden houses (Product as a Service) based on IoT	01/12/2022
3.	Test model for a use-case and conduct the analysis	15/12/2022
4.	Implementation of a conceptual model for the use case and conducting the analysis and visualization of performance parameters	20/12/2022

5.	Compiling the results and finalizing the thesis writing	30/12/2022

Language: English

Deadline for submission of thesis: "02" January 2023.

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CONTENTS

PREFACE

This thesis focuses on studying and offering a concept for prolonging the lifetime of Adapteo rental building modules by tracking them with IoT technology.

Thesis author Egle Vogt is the Product Manager of Adapteo Group. Adapteo Group is one of the biggest rental real estate groups in Europe. This thesis mirrors the rapid changes in the world's economy and is based on the author's daily work. That work is happening only thanks to our product management team, our inspired leader Jan Isgård and big thanks to Örjan Berg for his strong support and help on the construction site. I also want to thank my supervisor Kashif Mahmood, who believed in me and provided continuous support in thesis writing, and Alar Kuusik, who motivated me to stay focused on a complex subject.

Objectives

- To study and understand the concepts: LCA of wooden modular houses, the role of IoT for data acquisition and monitoring, CE driven through IoT
- To develop a conceptual model for LCA of wooden houses based on IoT
- To analyze and monitor the life cycle process of a modular wooden house and suggest a control mechanism for improvement that leads to CE

List of abbreviations and symbols

AI - Artificial intelligence

BIM – Building Information Modeling

BOM – Bill of Material

BTA – Brutto Total Area

CAD – Computer Aided Design

CE – Circular Economy

DfD/A – Design for Disassembly and Adaptability

DFSS - Design for Six Sigma [3]

ERP – Enterprise Resource Planning

ETAP - Environmental Technology Action Plan

EPD - Environmental Product Declaration (EN15804)

GWP - Global Warming Potential, climate impact for different greenhouse gases calculated in kg CO_2e (Thrysin, 2020)

HVAC – Heating, Ventilation, and Air Conditioning

IoT - Internet of Things

IPP - Integrated Product Policy

KPI – Key Performance Indicator

LCA - Life Cycle Assessment – compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.

PaaS - Product as a Service

PCR - Product Category Rules (EN15804)

PLM – Product Lifecycle Management

SHM - Structural Health Monitoring

CONSTRUCTION PRODUCT - item manufactured or processed for incorporation in construction works. [1]

SERVICE - intangible, described, produced and consumed at the same time, high level of contact with the customer, the use of unique knowledge.

GOODS - any object or objects of purchase and sale, product or service intended for sale.

MODULAR – composed of modules for easy construction or arrangement and adaptation or disassembly. [2]

MODULE – set of standardized parts or independent units. [2]

1. INTRODUCTION

This thesis was written in an era where humanity has reached the discovery of the most magnificent technologies that allow creating values and quality of life from hitherto unimaginable renewable resources while at the same time destroying our planet and assets on a bewildering and unprecedented scale. Living in a renewal time where a significant part of the business world recognizes that success begins with empathy and caring. At the same time, part of the world's public sector seizes power on dishonest grounds and often uses new technologies that do not yet have legal regulations they are responsible for.

The author of this paper studies the technologies that facilitate the low operational carbon emissions and **circular product design** targeted by Modules Houses provider Adapteo’s sustainability strategy. Designing new products and services is expensive and associated with many risks, the biggest of which can cause the product to quickly become obsolete and unprofitable, which is a big obstacle to the long-term life of a circular product. One such product design tool to avoid design mistakes is the Design for Six Sigma (DFSS) [3], which can be defined as any systematic approach to designing or redesigning any product or service. Six Sigma is a disciplined, statistical, data-driven approach and continuous improvement methodology for eliminating defects in a product, process, or service and is based on the fundamentals of quality management. Starting to use the DFSS design technique and a quick look at the basics of such techniques make it clear that it is essential to have data for its implementation. Triggered by this knowledge, there was a need to collect data and to understand data collection technologies and their compatibility with design and business applications. The main objective of this thesis is to study the use of the Internet of Things (IoT) for collecting data to achieve a digitalized systematic design system of long-term circular product - modules.

The tasks for this research are:

1. Study and define the concepts of the lifecycle of wooden houses, healthy wooden houses, performance indicators for wooden houses Life Cycle Assessment LCA [4], IoT sensors, data acquisition method, a digital dashboard for monitoring, Circular Economy (CE), IoT as a driver for CE
2. Understand the importance of IoT for data collection and real-time monitoring and describe the applications of IoT for LCA and CE
3. Development of IoT-based conceptual model for data modeling, analytics, and monitoring of wooden houses LCA
4. Implementation of a conceptual model for a use case and conducting the analysis
5. Comparison of results, suggestions for improvement, and future work

2. OVERVIEW OF THE COMPANY

Adapteo is a leading Northern European flexible real estate company making €231 M in sales in 2020. The turnover by the country for that year was: Sweden 52%, Finland 24%, Denmark 10%, Germany 8%, Norway 3%, and Netherlands 3%. By 2021 they had a total area of approximately 1.1 million square meters of module area in their portfolio and 505 employees. [5] By the end of 2022, Adapteo's grown to 1.3 million m², eight markets, and 600 employees [6]. Adapteo as a brand is new, but the experience stretches back more than 30 years. Adapteo was created in connection with Cramo Adapteo acquiring the Nordic Modular Group in 2018. In July 2019, the merged company was separated from Cramo, and Adapteo was developed [7].

Adapteo rents buildings, not in the conventional sense of rental real estate, but in a modular form, where the building is delivered to the customer at the required place for the required time, and at the end of the rental period, the building is removed, and the previous situation is restored. So Adapteo can provide clients with the greenest buildings as the most sustainable building is the one not built [8]. Adaptive reuse is familiar to architects and refers to a new use of an old building, giving buildings a new function, such as apartments or restaurants built in former industrial buildings [9]. Adapteo's adaptive reuse is the assembly and disassembly of buildings by modules. Mutually adaptable modules can be reassembled in a new configuration, and continued reuse can be repeated again and again. Adapteo's business model is Building as a Service, a model known as Product as a Service (PaaS) [10]:

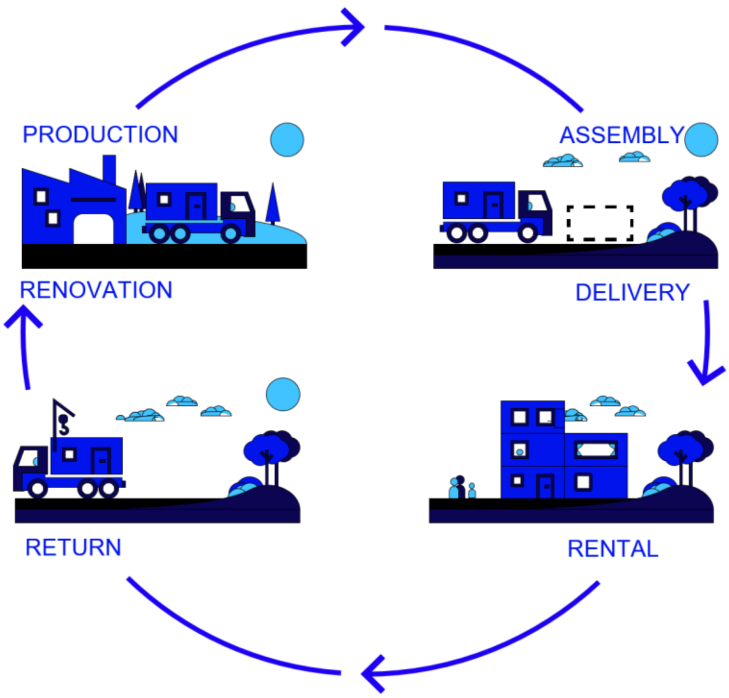

Figure 1 Adapteo circular business model (Adapteo Customer Presentation) [11]

Adaptable solutions are especially suited for improving social infrastructure, e.g., for daycares, schools, health and social care, and special accommodations. 65% of all Adapteo provided spaces are social infrastructure.

Adapteo's business area comprises CO_2-emitting sectors such as industry, transport, and buildings. The European Commission is developing rules for a new emissions trading system for the road transport and construction sectors [12]. The EU climate target cannot be achieved without reducing emissions from buildings and road transport. The new system will regulate fuel suppliers into sectors, which are responsible for monitoring and reporting the amount they put on the market. The emission limit will be established in 2026 [12]. Therefore, according to the Sustainability Report of Adapteo 2021, circularity is a solution for Adapteo and has been considered in the sustainability strategy. Seven out of ten Adapteo buildings were built by reusing modules in 2020 [13].

3. LITERATURE REVIEW

The basic science of this work has been strongly encouraged by Carlota Perez, Professor at the Institute for Innovation and Public Purpose, University College London. Similarly, as many economic decisions today can be based on empathy, Carlota Perez highlights the role of changes in people's lifestyles in driving innovation and economic growth. The Golden age of our current IT technological revolution is coming. Its potential will be shaped not only by government policies and business strategies but also by people's values and lifestyles. European countries have enough scientific and technological knowledge and innovation capacity to implement this Smart Green change to the Golden age. To achieve this, the Circular economy leads to a low-waste economy, focuses on preventive care and healthy lifestyles, increases energy and resource productivity, multiplies the creative economy, and promotes a shift from ownership to access and from material goods to immaterial assets. [14] Perez has said: *"Just as favoring suburbanization and the Cold War tilted the playing field in favor of home ownership, mass consumerism, and high-tech military innovation, we can now establish a bold set of policies aimed at Smart Green Growth and full global development. The first would favor services and intangibles and aim to reduce materials, energy, and transport, while providing a new aspirational good life aimed at health, caring, education, creativity, collaboration, and experiences and based on truly durable products, maintenance, recycling, reuse, and conservation. Pigovian taxation – punishing the 'bads'– and clear regulation have shown their effectiveness for tilting the playing field and creating synergies in chosen directions. Digital technologies, with their intangible and globalizing nature, provide the tools to do this while also modernizing the government itself* [15]. "

Empowered by the similar long-term work of Carlota Perez and many other researchers, Europe's and the whole world's understandings of shaping the future have increasingly guided the strategies of the Circular economy. The EU Circular economy action plan in March 2020 is one of the most vital parts of the European Green Deal. [16] Circular economy action plan chapter 3.6. "Construction and buildings" promotes circularity principles throughout the lifecycle of buildings by: "Promoting measures to improve the durability and adaptability of built assets in line with the circular economy principles for buildings design and developing digital logbooks for buildings." [16] On this basis, previous has been developed "Circular Economy - Principles for Building Design" [17].

3.1 Circular economy

Linear material and energy flows, i.e., linear economy, are not viable; therefore, the transformation of the economy into a circular economy is increasingly understood and directed through legislation in order to decouple economic growth from the use of natural resources and other finite assets. Circular Economy is defined as *"an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels. Attaining this circular model requires cyclical and regenerative environmental innovations in the way society legislates, produces and consumes"* [18].

Achieving a circular economy in the modular construction sector requires a significant and major change in product design and responsibility. For recycling, it is necessary to increase the quality of products and materials and increase the timely maintenance and restoration of products and materials. Turn to Adaptability is to extend the service life of the building as a whole, either by facilitating the continuation of the intended use or through possible future changes in use – with a focus on replacement and refurbishment. Adaptability prevents premature building demolishment by developing a new design culture to anticipate changes in requirements. Adaptability enables adaptations and transformations of the building for better use and reuses, new ways of using it, and preparing for the end-of-life and future lives of the building and its components. It is a conceptual and legislative approach compatible with Adapteo's goals and understanding of circular real estate operation. Standard ISO 20887:2020 gives the principles and guidelines for Design for Disassembly and Adaptability (DfD/A) [2]. DfD/A principles are a good framework for the design of wooden modular houses.

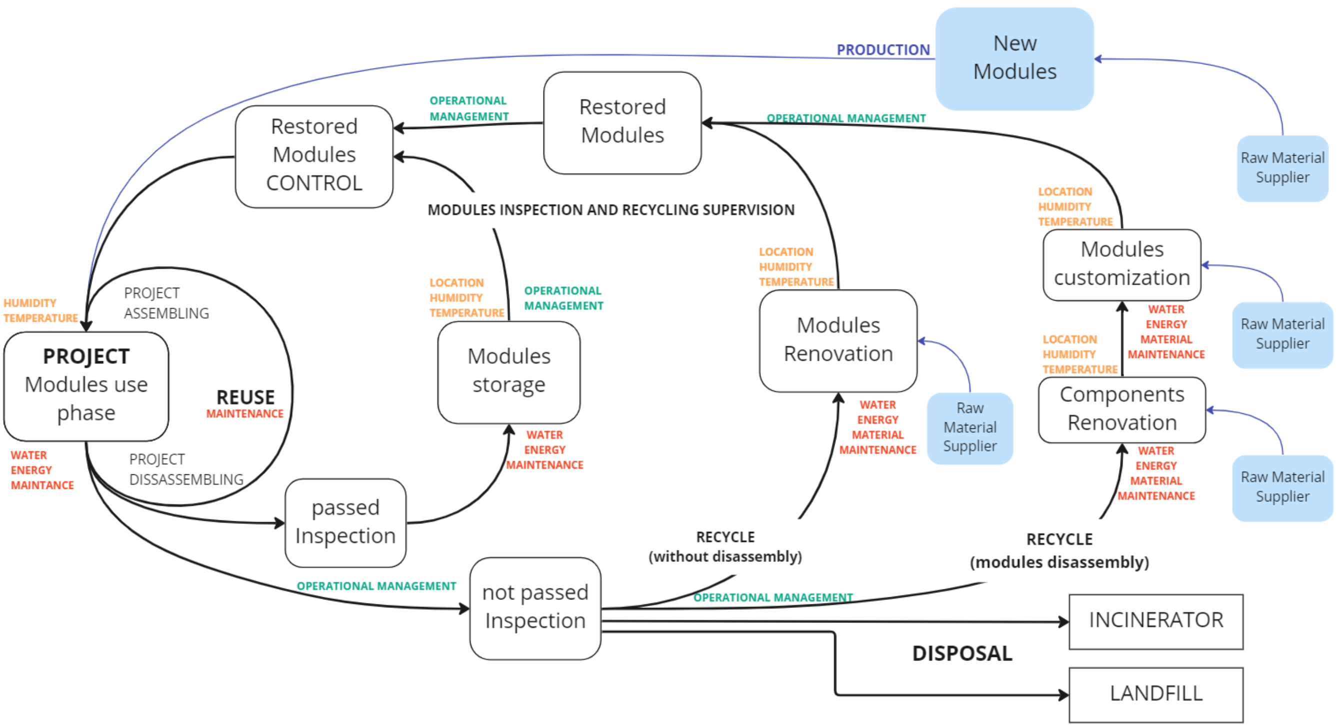

Figure 2 The Ricoh Comet scheme [50] adapted to circling of wooden house modules

From the custom comet diagram Figure 2, it can be seen that the complexity of operations and inventory management expands with each successive expanding cycle of use. In addition, managed data is generated from product history and product improvement developments during the product's life. Different product generations and changing legislation require product redesign and mapping and archiving of data. The standards guiding the life cycle management and assessment define the objectives and questions of these operations management to be answered and describe in detail the object of the LCA accruement, i.e., the exact product or system to be analyzed. Adaptability and continuously reusing system management successful implementation is possible only by quality decisions based on quality data in real-time. The steps in a real data flow are collecting the data, understanding the data, and using the data. This work follows the data flow described in Figure 3.

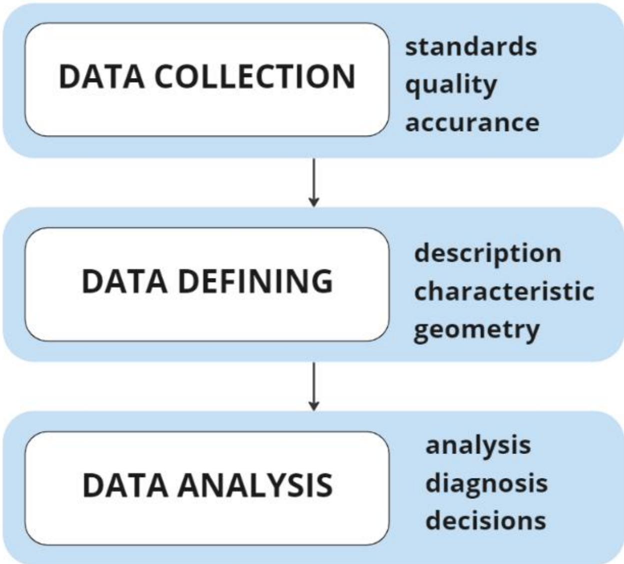

Figure 3 The data flow of circular product

The primary condition for a circular use of materials or goods is to have information about the existence of these goods or materials. Materials or products with enough reliable information about safety, age, technical parameters, documentation, geometry, environmental impact, etc., are allowed to be used during system design. In addition to the data pertaining to material condition, a lot of data is created during product development, planning, and creation, which needs to be stored and kept during the product life cycle.

3.2 Method for Data collection - IoT

The main premise of the circular economy is data. In circularity, only the use of those products and goods we are aware of is possible. For reuse in the design and planning of the used materials or goods, accurate characteristics, geometry data, product history, and all previous designs are needed. In order to fulfill this task, monitoring and recording the design, production, transportation, use, maintenance, conversion, certification, and decommissioning data of each product during its lifetime is needed. Understanding the volume of such monitoring and control processes seems impossible and unnecessary, but already-existing technologies like the Internet of Things (IoT) help to solve this complex task intelligently. [19] The IoT Technology allows collect and storage the precise and accurate data and places this data in the right place and time. A comprehensive overview of the research conducted on the interdependence of IoT and the circular economy is provided by: "The Internet of Things and the circular economy: A systematic literature review and research agenda" by Abderahman Rejeb, Zailani Suhaiza, Karim Rejeb, Stefan Seuring, Horst Treiblmaier [20]. Connecting things into a single intelligent network supports the monitoring of products and components throughout their life cycle and enables smart decisions to be made in real-time for better preservation, maintenance, and use of products, materials, and components handling. Abderahman Rejeb, Zailani Suhaiza, Karim Rejeb, Stefan Seuring, and Horst Treiblmaier explore how the intersection of IoT and CE has been addressed and what the main emerging research topics and their interconnectivity are. Their study provides a wide range of understanding of how the Internet of Things can advance and sustain CE goals and provides evidence that adopting IoT technology supports organizations' circular strategies and facilitates value creation. The study covers a wide range of representative papers that reflect the current state of IoT and CE research discourse and helps researchers and entrepreneurs understand the connections between IoT and CE.

- IoT advantages are intelligent and autonomous, enabling communication between machines and the ability to define the location, condition, and availability of tracked assets.
- Disadvantages are structured data interoperability and scalable compatibility

IoT technology enables new business models, is an essential helper in the design and control of LEAN processes, enables intelligent maintenance and management of products and components during the period of use, and allows quick and high-quality feedback to product and service designers enabling the development of brand loyalty. IoT is the connection between the physical and digital worlds.

One goal of IoT technology will be to create reliable Digital Data for the product, as the basis for right decisions. Thanks to the collaboration of the European Union and research institutions, the technologies also reach the regulations, and the requirements and recommendations for the digitalization of product data are under discussion in the law-making work. In the press release of the European Commission, "Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence" March 30, 2022, the sustainable product Ecodesign Directive [21] European Commission made a new proposal: "All regulated products shall have Digital Product Passports" [22]. In the product system, LCA goals and scope must be specified. Data quality guidelines and requirements are described in the ISO 14044:2006+A1+A2:2020 [23]. Data quality requirements should address the age of data, geographical area, precision, percent of completeness, representativeness, consistency, reproducibility, sources, and information uncertainty. Data quality requirements are set in standard EN 15804:2012+A2:2019. According to the very good quality level, the processes included in the data set fully represent the geography stated in the location indicated in the metadata. Data Time representativeness should not be older than 0 years. [1]

3.3 Methods for Data defining - CAM, BIM, Digital Twin

Smart products use multiple technologies, and therefore most changes require the development of technology in all areas simultaneously. Computer-Aided Design (CAD) tools used in the manufacturing industry are CAM (Computer Aided Manufacturing) applications. In construction, design is widely done in CAD based on Building Information Modeling (BIM). All these modeling processes providing the model of the goods, items, machinery, building, etc., can be easily changed to digital twins. The information necessary for producing products, machines, and buildings has become accurate enough to visualize complex and realistic objects. The IT capability to generate from already existing information a digital twin ecosystem opens new application possibilities for monitoring products during the use, maintenance, or repair of products, machines, or buildings in a realistic digital "meta world" and playing scenarios out in simulations. Realistic visualizations combined with real-time monitoring lead to a measurable competitive advantage. Modifying static models by changing their parametric indicators revives 3D objects and turns them into dynamic digital twins offering many new possibilities, the introduction of which creates unfathomable possibilities for enabling intelligent management. The aim of Digital Twins is the synchronization of the real world and virtual world for seamless management and control of the product bill of material (BOM), Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), Life Cycle Assessment (LCA), and other life cycle processes of the built environment [24]. To achieve this, data is needed, and IoT technology aims to collect that data. Min Deng has collected and conducted a systematic review of published research on the development of this technology. The review is based on 100 articles on which a taxonomy based on the life cycle of buildings was developed. Based on BIM, it was possible to construct an E-energy simulation and user behavior simulation with detailed geometric information to manage the sustainable use of the building. In his work, Deng has outlined the levels from static BIM usage to the ideal Digital Twin concept. The integration of BIM with IoT is on the middle or third level in this scheme (Figure 4). Relying on CAM models can give real-time insight into detailed product material and cost information and sustainable monitoring and control simulation. Min Deng has pointed out that more studies have been done on the stages of design and construction, and few studies are related to the stages of building maintenance, modernization, and demolition. [24] Buildings assembled from IoT-trackable modules can be included in real-world locations in Digital Twins of Cities. Module tracking allows simulation processes and transport of modules in cities, warehouses, ports, and roads.

Level 1	BIM Review
Level 2	BIM-supported Simulation
Level 3	BIM integrated with Sensors IoT
Level 4	BIM integrated with AI
Level 5	Ideal Digital Twins Concept

Figure 4 Evolution of BIM to Digital Twins in the Built Environment [24]

This work focuses on the collection of data necessary for the integration of IoT technology and 3D product models described in the Level 3 stage. Based on collected data, real-time visualization in 3D digital models could be used in making timely decisions and changing the design process in any phase of the product life cycle. It also provides opportunities to continuously control the use of the building in the best and most energy-efficient way and provide an automated report of real Data of GWP during a lifetime.

3.4 Method for analysis - Life Cycle Assessment

Product designers, manufacturers, and product owners of construction products in the EU construction sector are obliged to have and provide the information that will enable them to make decisions to lower the environmental impacts of buildings and other construction works. Variable voluntary and mandatory tools are available to achieve this objective. The EU provides tools such as economic instruments, substance bans, voluntary agreements, environmental labeling, and product design guidelines. A comprehensive overview of regulations is provided by Serenella Sala, Andrea Martino Amadei, Antoine Beylot & Fulvio Ardente in the article "The evolution of life cycle assessment in European policies over three decades" [25]. Integrated Product Policy (IPP) looks at all phases of a product's life cycle and seeks to minimize the environmental effect where it is most impactful [26]. Implementation of the IPP communications includes the European Platform on Life Cycle Assessment (LCA). Life Cycle Assessment (LCA) is a standardized methodology (ISO 14040 ff) that considers the entire life cycle of a product to evaluate the environmental impact, environmental benefits, compromises, and areas for achieving improvements related to goods and services (products) [26]. The information gathered from LCA reports supports EU policy in establishing eco-design criteria, such as contributing to the performance targets of the Environmental Technology Action Plan (ETAP), the ETT Directive in Green Public Procurement (GPP) for energy-consuming products and in Environmental Product Declarations (EPDs) [26]. The common language for assessing and reporting on the sustainability performance of office buildings provides the European framework "Level(s)" [27]. EPDs provide quantified environmental data for predetermined indicators using verified Life Cycle Assessment (LCA). Published by the European Committee for Standardization (CEN), EN 15804 suite of standards includes:

- Framework level (EN15643 -1,2,3,4,5) 1400
- Building Works Level (EN15978, EN16309, EN16627)
- Product Level: EN15804 + A2 – Environmental Product Declarations – Core Rules for Construction Products; EN15942 – Environmental Product Declarations – Communication format business-to-business; CEN/TR 15941 – Environmental product declarations. Methodology for selection and use of generic data; CEN/TR 16970 - Guidance for the implementation of EN 15804

Adapteo LCA Report analysis

The IVL Swedish Environmental Research Institute has assessed climate sales of the Adapteo product and business model in Report U 6536 Climate impact assessment of a modular building [28], a report taken as the basis for the design and study of this thesis. Product Category Rules (PCR) by Building Materials Standard (EN15804) do not have the PCR for building modules. Without a PCR, the boundaries of a system are specified for the LCA calculation and contain an explanation of which life cycle stages are included according to the life cycle stages of the building or construction material shown in Figure 5.

System boundaries																
A CONSTRUCTION stage					B USE stage							C END OF LIFE stage				D Benefits and loads beyond the system boundaries
Product stage			Construction process													
Raw material supply	Transport	Manufacturing	Transport, and storage of products	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-Recovery- Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
x	x	x	x	x	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI

Figure 5 LCA-stages according to EN15978 (buildings) and EN15804 (construction materials), x marks which LCA-stages are included. [28]

In the traditional construction sector and permanent buildings, the lifetime stages in LCA follow the linear realization from the cradle to the grave (Figure 6). Recycling and circularity are possible for materials able to separate cleanly and reproduce, recycle, or use in energy or landfill.

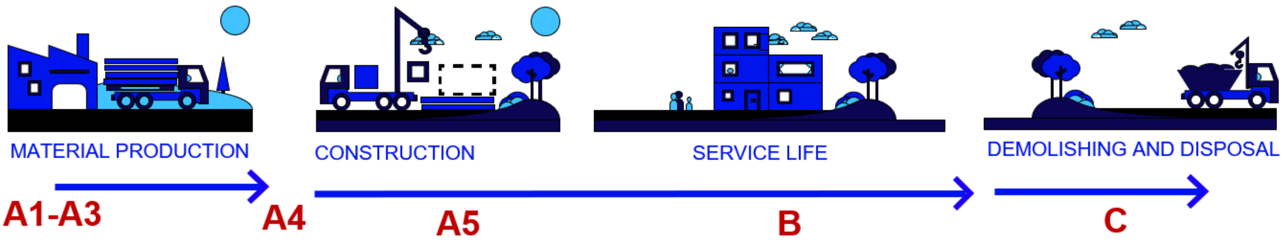

Figure 6 LCA-stages on traditional building construction and lifetime model.

In the Adapteo business model (Figure 7) and in the LCA calculation of Adapteo modules, the stages that follow each other change their positions, and the constant monitoring and control of this is troublesome to define. The IVL report considers the building modules produced in Estonia. The lifetime of the module is **25 years**, and the buildings are used in Sweden. In the transport stage, transport from Estonia to the first project and predictable transport between future projects is considered.

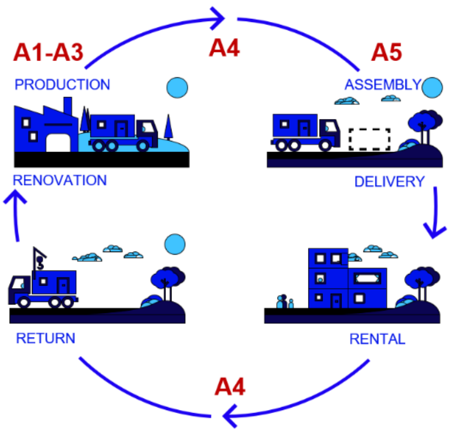

Figure 7 LCA-stages on Adapteo business model (marked only the stages considered in IVL report). [28]

A1-A3 is the production stage in Estonia and for the material needed to renovate the modules between different rental periods.

A4 is transporting the new modules from Estonia to Sweden and delivering them to the next project site. (The distance between projects is set to 330 as the average distance between Adapteo projects.)

A5 is energy use at the production site for project assembly.

For this report, the life length of the modules and other reused materials is 25 years, and the project use phase is three years.

Table 1 The climate impact with the total use phase of three years; the result is shown in total GWP as well as GWP per BTA (Brutto Total Area) for each LCA-stage.

Results	
Total GWP (kg CO_{2e})	22 234
Life cycle stage	GWP/BTA (kg CO_{2e}/m^2)
Product stage, A1-A3	30
Transport to project site, A4	7
Construction process, A5	2
Total A1-A5	**39**

The results (Table 1) from the climate impact assessment show that the construction materials of the modules stand for 56% of the project's Global Warming Potential (GWP) and the transport to the project site for 17%, see Figure 8.

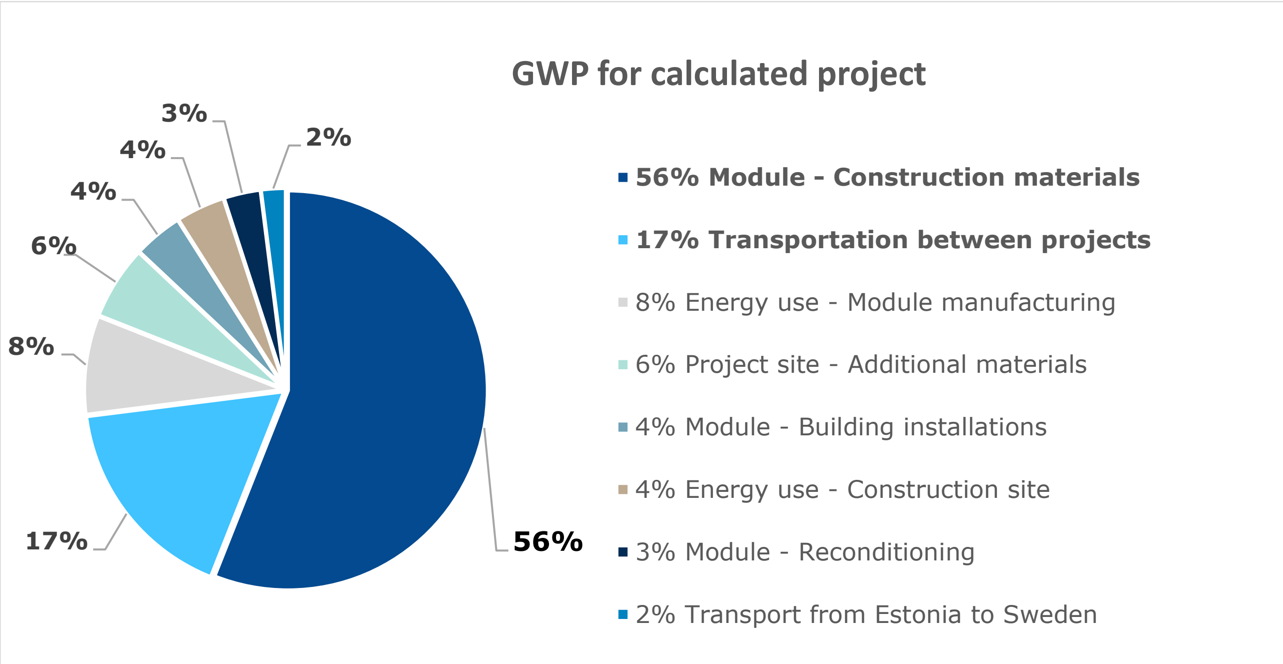

Figure 8 Climate impact divided between different activities.

Adapteo C90 System has 14 main module types. The GWP per gross floor area (BTA) for the different module types varies between 176 and 217 kg CO_2e/m^2. Calculations take into account building construction materials, production energy use, transport, reconditioning and additional materials and energy use in the assembly site and installation. GWP by module type depends on the amount of exterior and inner walls and the doors and windows.

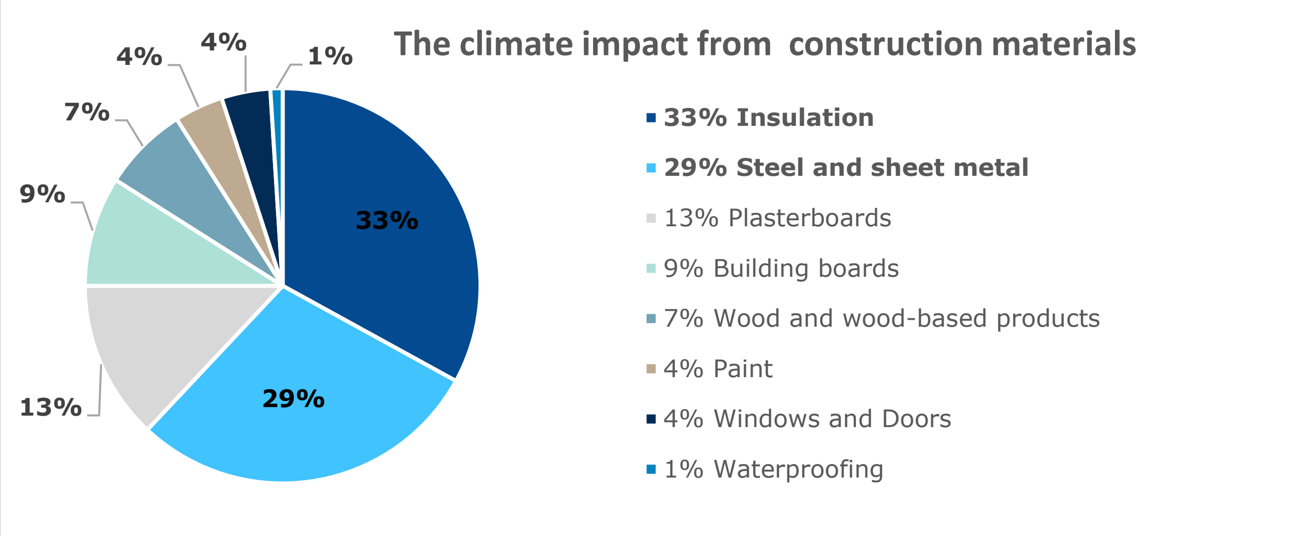

Figure 9 The climate impact from building modules of the specific building project divided between different construction materials.

Insulation, steel, and sheet metal stand for more than 60% of the GWP, considering modules used in the project, see Figure 9. Whereas building and plaster boards account for approximately 20% of the GWP for new modules. Sensitivity analysis of IVL reports analysis confirms that the building use phase length and lifetime of the module have a significant effect on the GWP of the modular building.

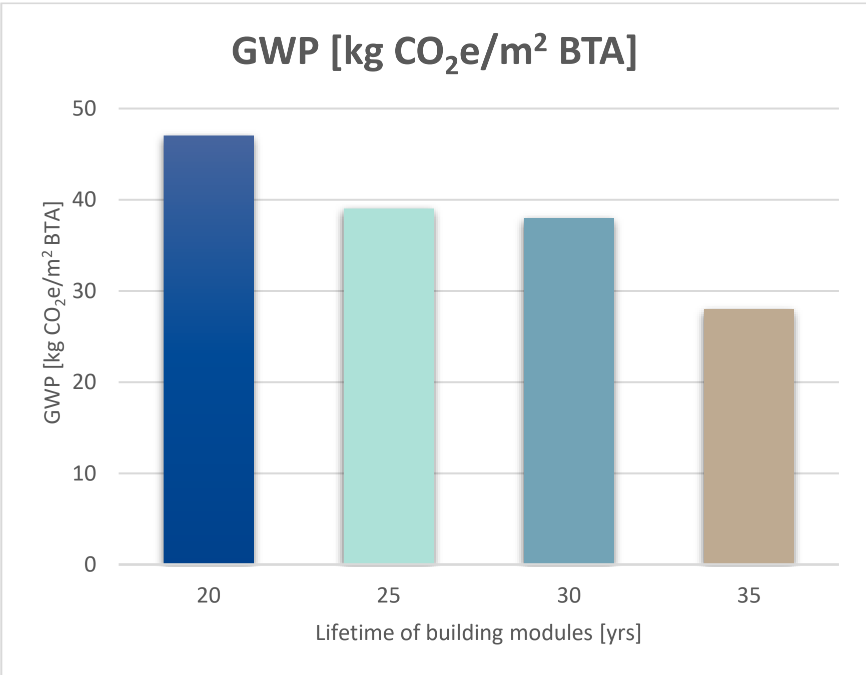

Figure 10 Climate impact depends on module lifetime; the project duration is constant and set to three years.

The results show that the GWP decreases by 25% with 10 years longer module lifetime (Figure 10). This indicates that for Adapteo to lower their climate impact from their projects, one important factor is the life length of the modules. And second Sensitive test shows that the climate impact from using the modules decreases with a longer use phase.

Adapteo's conclusions from the LCA and future goals:

- **Prolonging the lifetime** of a building by ten years can reduce the climate impact per use by approximately 25% (25 years compared to 35 years).
- **Multiplying the uses** of a more durable and better maintained smart product
- Key areas to work with to reduce climate impact are choice of materials, **reduced transport between projects** and energy use at production and project site.
- Adapteo should **prolong the rental periods**, extending a 2-year contract to three years has a bigger impact than prolonging a 5-year contract to six years.

Prolonging the wooden houses' lifetime is the key objective of sustainable construction development. Carbon Capture, Use, and Storage (CCUS) is considered as one of the available options for reducing emissions and using captured CO_2 in chemical products, building materials, or processes for conversion to fuels [29]. Designed wooden buildings' lifetime is 25 to 50 years, but the cutting age of high-quality construction wood is, on average, 100 years. Responsible, sustainable economic activities and species diversity protection require using one felled tree and the CO_2 associated with it for 100 years. Types of destruction and damage to wooden buildings are humidity, mold, fire, and tension. In addition, a lot of damage occurs to modules during transport, storage, and building installation, as part of the indoor structure is exposed to outdoor conditions during these stages. The average felling age of Pine is 100 years according to Estonian Forest Management Law (Table 2).

Table 2 Felling ages by Estonian legislation: Forest Management Law RTL 2007, 2, 16 [30]

Tree species	The felling ages (years) by *site quality class*					
	1A	1	2	3	4	5; 5A
Pine	90	90	90	100	110	120
Spruce	80	80	80	90	90	90
Birch	60	60	70	70	70	70
Aspen	30	40	40	50	50	–
Alder	60	60	60	60	60	60
Oak	90	90	100	110	120	130

Today's general awareness considers wood as a renewable and environmentally friendly building material in terms of sustainability. In addition, an essential aspect of why the EU considers wood to be the most environmentally friendly is that wood binds and stores CO_2. Wood can be CO_2 negative material.

- ✓ Carbon accounts for approximately 50% of the dry mass of trees. [31]
- ✓ During the growth, the trees bind carbon, and each cubic meter of wood binds about one ton of CO_2 for. [32]
- ✓ Carbon stored in wood is only released back into the atmosphere when the wood product is burnt or decays. [31]

To preserve forests' ecosystem and species diversity, carbon must be stored in wood, and the modules' lifetime must expand as long as possible but at least over the tree maturity age of 100 years.

Reference Service Life (RSL) is the expected service life of a component under a particular set, i.e., a reference set, of in-use conditions and which may form the basis of estimating the service life under other in-use conditions. Reference service-life data (RSL data) is information that includes the residence service life and any qualitative or quantitative data describing the validity of the reference service life. [23] In the construction product design standards are required to design the Working Life. Reference service life can be the same as designed working life. Working Life is an assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair necessary. [1]

Three key criteria are used for adaptive reuse decision-making: capital investment, asset condition, and regulation [33]. In order to increase economic benefit through reuse and recycling, it is important to avoid a decrease in the asset condition. Predicting future damage of material and to discovering weaknesses of design and in usage management control is also necessary. In the context of this work, the damage is defined as a change in material characteristics or geometry that negatively affects the use of the material in the preexisting system or the use in the subsequent system. This can be achieved by Structural Health Monitoring (SHM) [34]. It is important to prioritize the design of the tools that can detect potential damage in inaccessible locations. LCA stage B2 requirement is preventative and regular maintenance. It means planned servicing, cleaning, recovery, or replacement of the damaged or degraded parts of the product during the product's RSL. If the LCA service period is longer than the material's RSL, it should be considered in LCA assessment. The reference service time (RSL) of the product is important in evaluating the use phase. In a cradle-to-grave assessment, many materials and components will need maintenance, renovation, or replacement. The manufacturer notifies PCR. Considering the RSL, it must be taken into account that it depends on the use of the product and the reference conditions of the use stage. RSL must be verifiable. Service Life is the period of time after installation during which a building or its parts meets or exceeds the performance requirements [35]. Building working life is shown by design working life category is shown in Table 3.

Table 3 Indicative design working life [36]

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures*
2	10 to 25	Replaceable structural parts, e.g., gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental buildings structures, bridges, and other civil engineering structures
* Structures or parts of structures that can be dismantled with a view to being re-used should not be considered temporary.		

4. IOT CONCEPT FOR LIFE CYCLE ASSESSMENT OF WOODEN MODULAR HOUSES

Methodology

In order to understand IoT capabilities to monitor the product and mitigate any kind of risks over its lifetime, a test case study was developed. In this test case, conditions inside the walls and inside the rooms will be monitored for proofing a concept of IoT driven Circular module system through the development methodology as shown in Figure 11. The test case aims to prevent damages and prolong the lifetime of modules through monitoring the conditions.

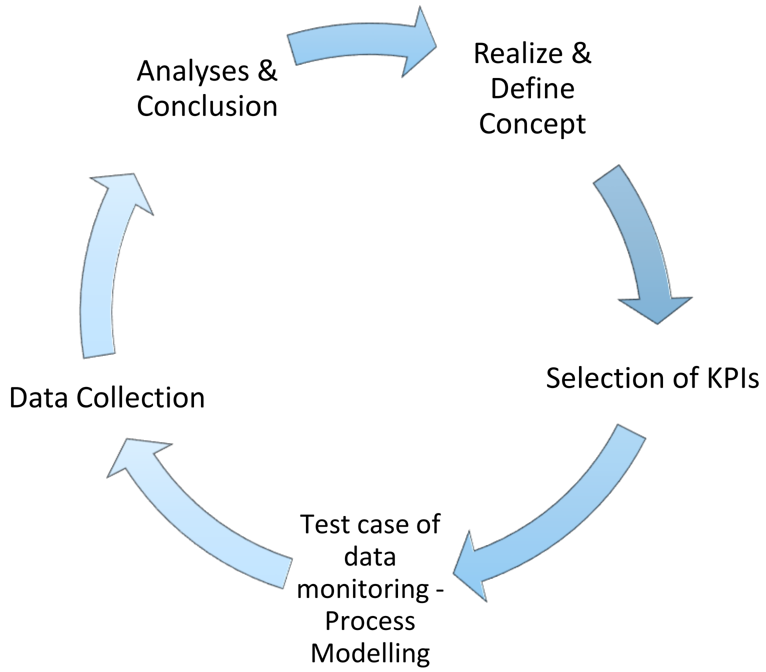

Figure 11 Continuous flow diagram of the methodology

1. **Realize & Define Concept** - The first step is describing the IoT driving Concept of Circular wooden Modules and the goal and scope of the concept.
2. **Concept Modelling and KPIs** – The second step is defining the interrelationships between the key environmental indicators as key performance indicators (KPIs) that cause damage of wooden construction. A description of the occurrence of an unfavorable situation, the mechanism of its work, and a solution to manage and improve the problem will be proposed.
3. **Test case of data monitoring - Process Modelling** – Design System models, Software Models, and Hardware models for focused study case of prevent damages inside the walls.
4. **Data Collection** – Selection of sensors and platform. This step will investigate the different existing providers and technologies. Analyses of the systems and solutions will be made before

the final decision. Data collection and analysis and the further use of the collected data and the most appropriate forms of data use offered.

5. **Real-time Monitoring and Visualization** - Monitoring and evaluation of collected data for automatic transfer of data to the indoor climate control system.

4.1 Realize and defining the IoT Concept for LCA of wooden houses

The designed concept is combined from Life Cycle management framework LCA and IoT technology. In the design and define of the IoT concept the conlusion of Adapteo LCA report, the General EU regulations and ISO standards are taken into account. According ISO standard EN ISO 14044:2006 guidelines [23] an LCA shall include the four phases of LCA framework. The LCA framework is used in realizing and defining of concept as design guidline of the concept and relations and phases is taken account (Figure 12). The interpretion phase is used as concept design and defining phase.

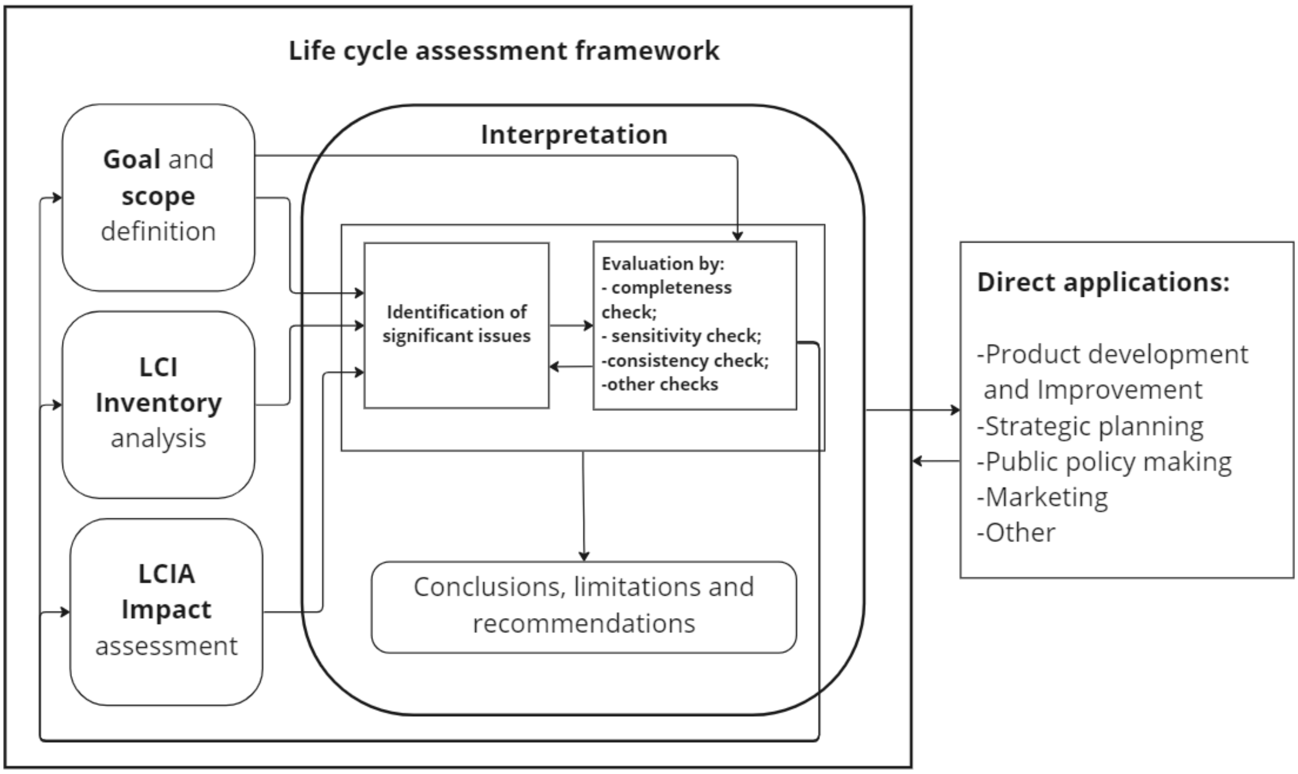

Figure 12 Relationships between elements within the interpretation phase with the other phases of LCA (EN ISO 14044:2006) [23].

Goal and Scope

The Goal of this study is to propose an automated Product Lifetime Management (PLM) system of wooden modules and data collection pool for future AI and Machine learning tools.

The Scope of IoT Concept study:

- The product system to be studied – **Standard Module of the wooden modular house**
- The function of the product system – **Constuction component, building product**
- The functional unit - **One MODULE during one rental project in one place**
- The system boundary - **LCA A4 to D stage calculations and seconadry use**
- Allocation procedures - **Production, Transport, Assembly, Use, Reuse**
- Interpretation of be used - **Prolonging the lifetime and calculation of befits**
- Data requirements - **Real time, GPS monitoring, Big Data for AI**
- Acceptions - **EU Construction Product Regulations (CPR)** [37]
- Value choices elements - **Structural Health Monitoring (material quality)** [34]
- Limitations - **EU region + Norway**
- Data quality requirements - **age of data, geographical area, precision** [23]

Life Cycle Inventory analysis (LCI) of IoT Concept study

Inventory analysis is the second stage of life cycle assessment. This work creates a model for data collection and sampling for selected sample indicators. The main task is to model the tracking system of the product system. According to EN ISO 14040, inventory analysis includes "data collection and calculation procedures to quantify the relevant inputs and outputs of the product system.” This paper defines the proposed data collection method and stages in the LCA model.

In order to better understand this goal, the life map of a traditional building (Figure 13) and the life map of a standard modular building are compared.

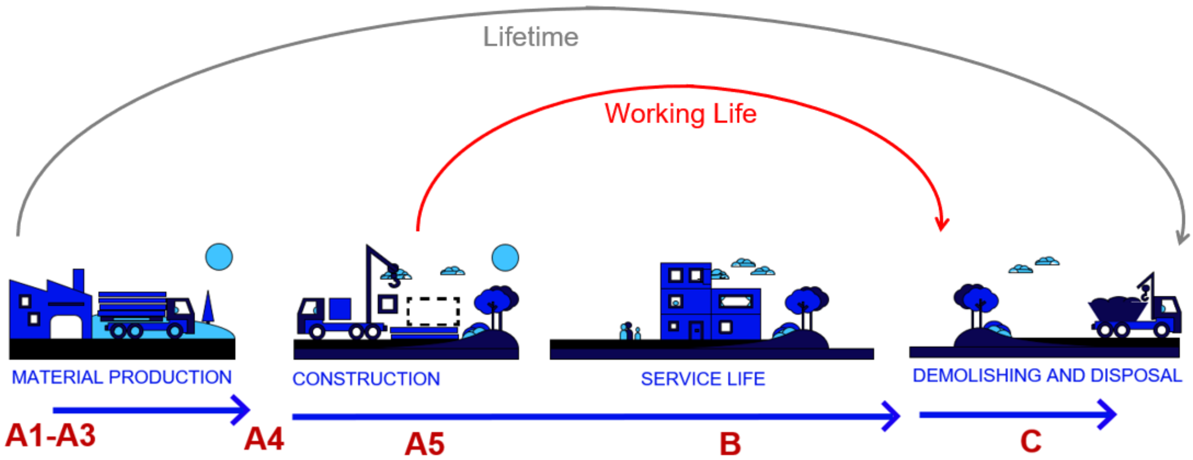

Figure 13 LCA-stages and the working life on traditional building construction and lifetime model.

The life map of the standard modular building (Figure 14) shows that the length of the entire lifetime depends on the service quality, the conditions of the working time and the conditions in storage and transport stages. Properly maintained and wisely designed buildings can loop in their working life for a very long time .

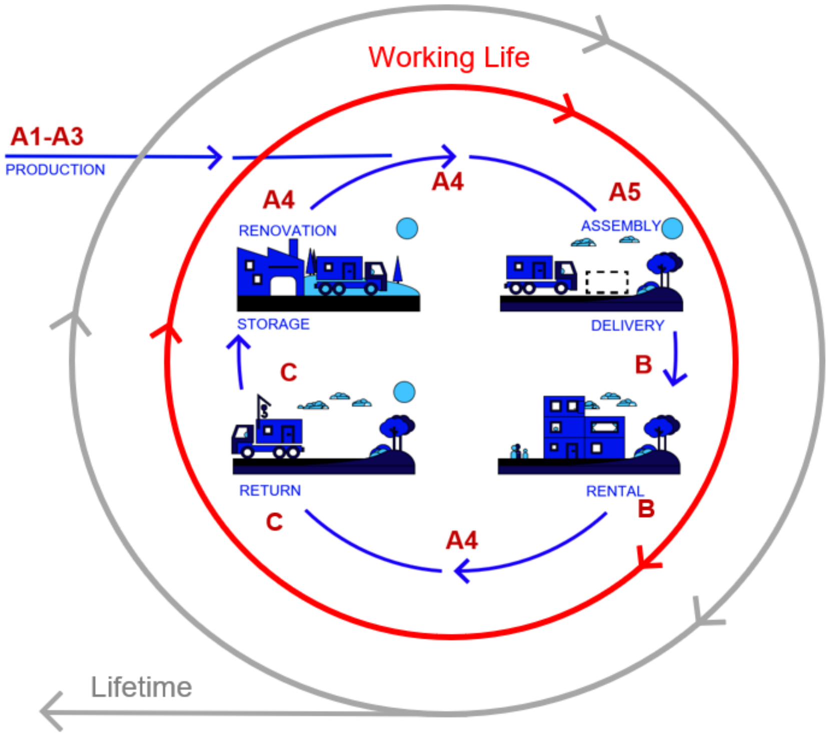

Figure 14 LCA-stages and the working life the life map of a standard modular building.

Based on the previous literature review, PLM is possible and realistic when modern technologies are applied. Proper design, operation, and maintenance are easily controlled based on the data obtained in the field, which can be visualized by a three-dimensional simulation of the real situation. Real Data and visualization provide here an opportunity to use high value adding design tools like Design for Six Sigma (DFSS) and Design for Disassembly and Adaptability (DfD/A) principles. Product digitalizing and monitoring in all processes are complicated, and it requires working in one platform to combine a lot of different forms of data. In Figure 15, the data collectible by sensors is shown in red.

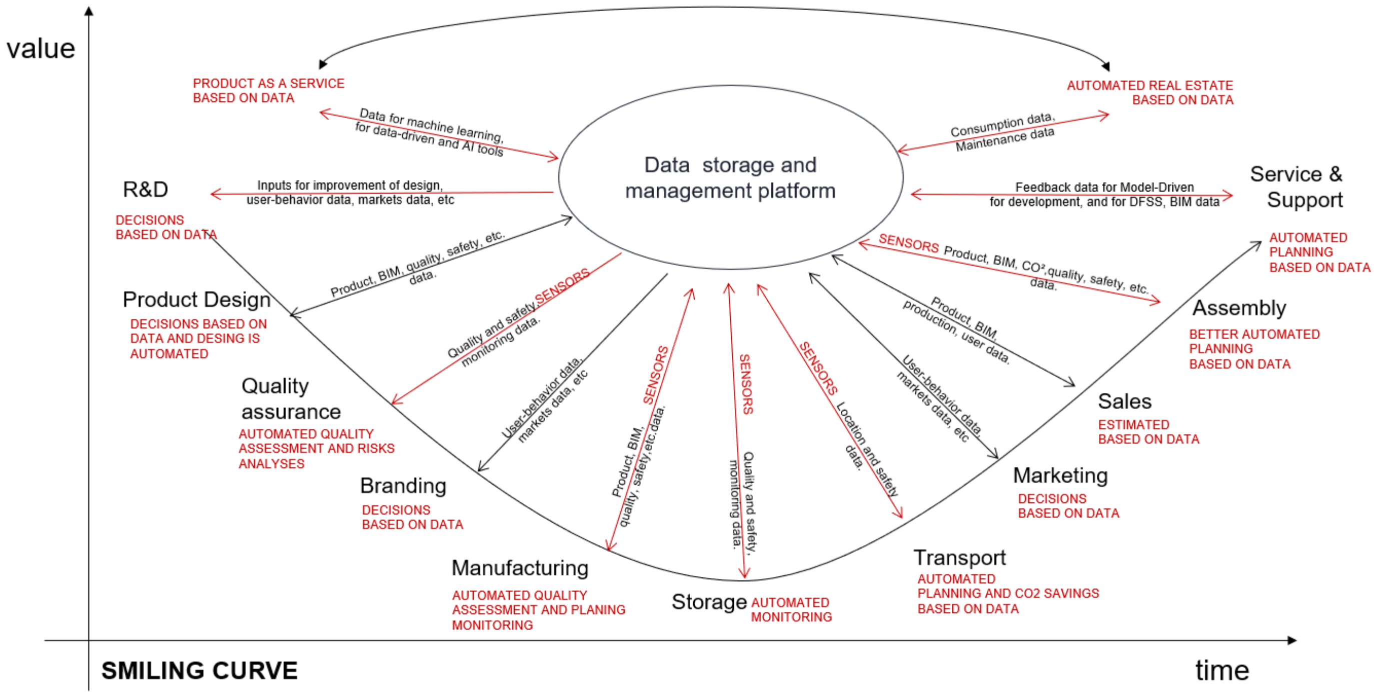

Figure 15 IoT Monitoring of modules on the Shih's Smiling Curve of Product as a Service by Ryan Dingler [38].

Life Cycle Impact Assessment (LCIA) of IoT Consept study

The third stage of life cycle assessment is the Impact Assessment, during which the data is associated with specific environmental impact categories and category indicators, with the aim of understanding these impacts. LCIA includes mandatory elements (selection of impact categories, classification, and characterization) and optional elements (normalization, grouping, weighting). This work links together Adapteo's business model, LCA defined stages and monitored data flow to create a circular product life management. [29]

Life Cycle interpretation of IoT Consept study

The fourth and final phase of life cycle assessment is interpretation. The interpretation assesses the compliance of the inventory analysis and impact assessment with what is defined in the objective. [29] In this work, interpretation is modelling a system concept in interpretation that considers definitions of purpose and scope.

The proposed IoT Concept of LCA (Figure 16) is a continuously circling data-driven management system. The functional unit is one module per rental period in one location, one life circle. The systems boundaries are the same as the rental project boundaries, and the loads and benefits calculation (module D) is correlated with the project's boundaries. The hypothesis is that the use of IoT real-time monitoring prolongs the lifetime of Adapteo Modules, reduces the routes between projects, minimizes waste, and triggers the data-driven circular business model PaaS (Product as a Service). The renovation works and redesign of each circle are saved in the BIM (Building Information Modeling) model based on extensive and accurate data, which is flawless and efficient Interactive product description for all stakeholders in all product stages.

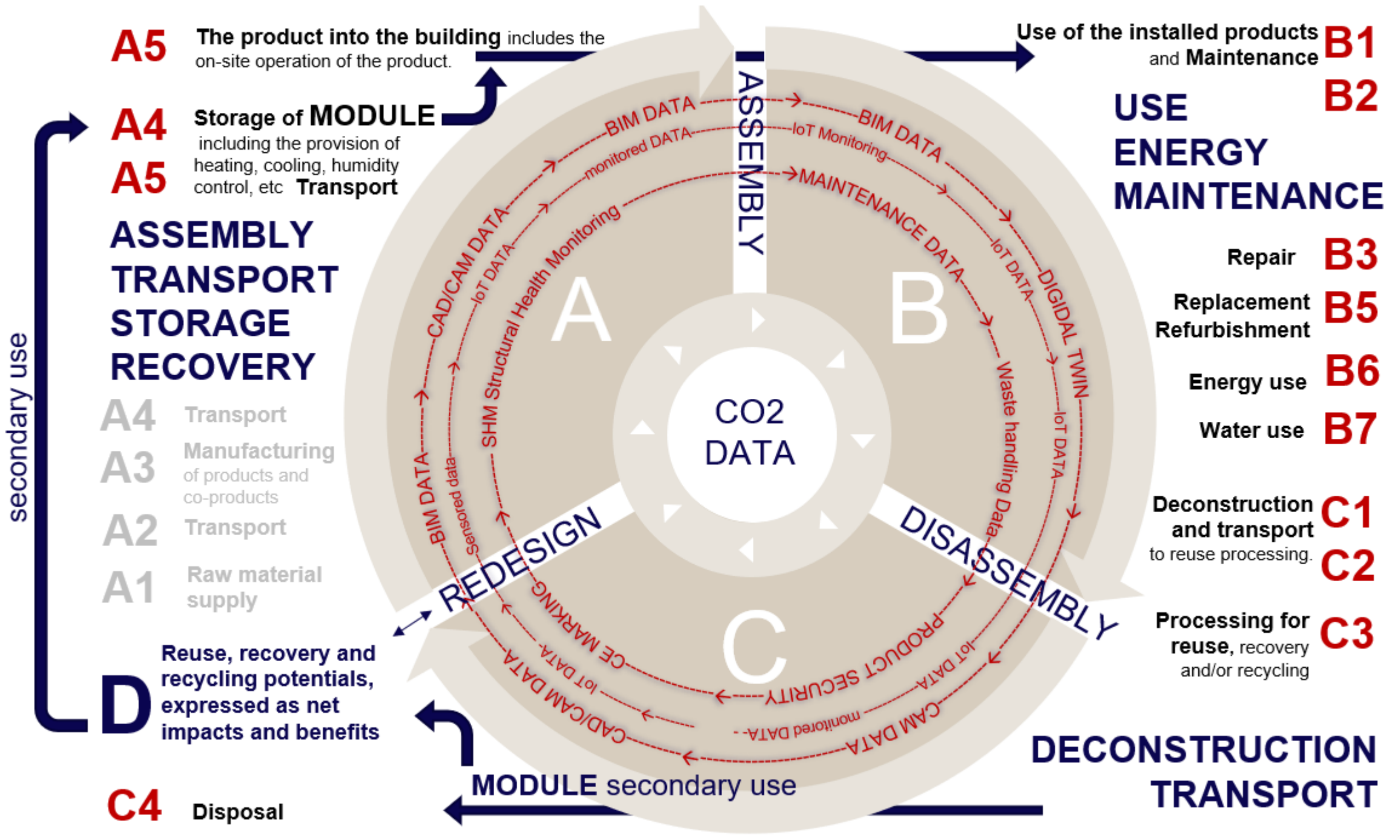

Figure 16 Conceptual IoT model for LCA of Modular wooden houses (Product as a Service)

The key point of the model is the D module, where each case of the next life cycle is designed according to the LCA D module formula [1]:

D module formula from EN15804 + A2:

$$D_{\text{loads and benefits}} = (\text{MATERIALS}_{\text{out}} - \text{MATERIALS}_{\text{in}})\ \text{QUALITY}_{\text{ratio}} + \left(\text{Waste}_{\text{for enegy use}}\ \right)$$
$$+\left(\text{Waste}_{\text{burned in last system}}\ \right) + (\text{Waste}_{\text{incinerated}}\ )$$

The sensors and the connection are selected by studying and comparing the available technological options. During the study test, the data collection platform is not created, and if possible, the environments provided by the communication service provider are used.
During the production, storage, transport, and assembly phase, the modules are not connected to the power grid, which means sensors must be working on battery power. During the rental period, the data output is much larger, and modules are connected to the smart power grid. The connectivity varies during the different stages of life. In the current Concept model, it is crucial to build an ecosystem where all modules are monitored (product monitoring), as opposed to building monitoring (project monitoring). The functional unit is one MODULE. In the mobile operating phases, such as transport, storage, etc, the data mount is low and suitable for the use of low-power wide-area network (LPWAN). LPWAN is a radio technology standard developed by 3GPP for cellular devices and services. The Narrowband Internet of things (NB-IoT) is LPWAN [38]. During the Rental Period, modules are connected to each other with the Power Smart Grid and a 5G network. During the use phase, it is possible to use more sensors and cameras and other energy-intensive sensors included in smart building systems and smart city systems. The correlations of the explored technologies with the LCA steps are shown in the Concept model in Figure 17.

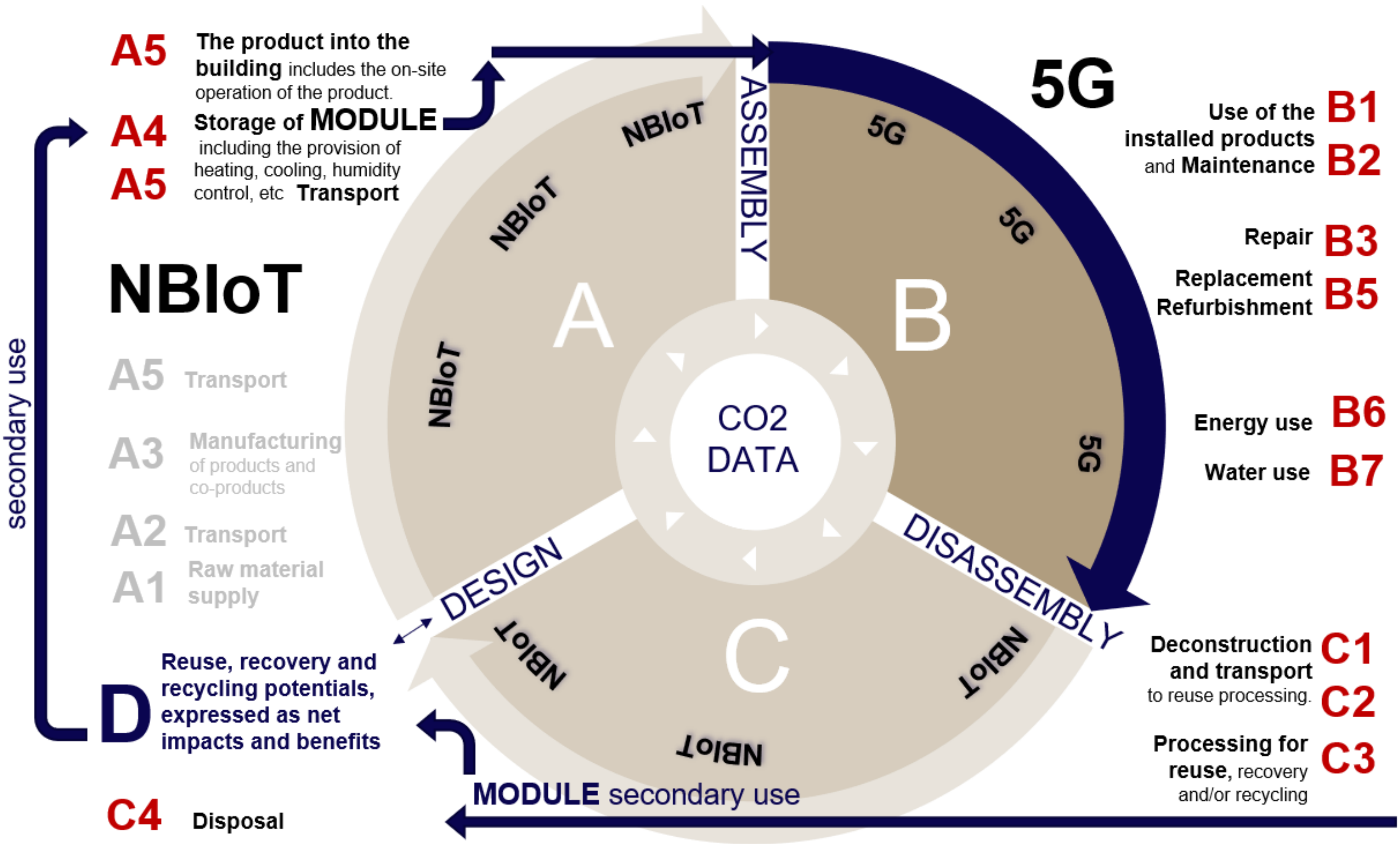

Figure 17 IoT Network types in concept module LCA phases

Databases of collected Big Data during a product's long life must be designed in an adaptable parallel way and allow the capability to construct correlations between measurements. Product (MODULE) tracking will be built on quality management, sustainability, design principles, and requirements to get data for redesigning the processes and taking preventive actions for improvements in the business and sustainability achievements.
The homes, rooms (BUILDINGS), and City tracking are aimed at energy-saving and the space using tasks. Smart Buildings and Smart Cities projects and technologies focus on managing resources and providing better solutions with fewer inputs. B-stage product monitoring will get a lot of data from these systems and vice versa.

Additional Concept Benefits:

- ✓ Reducing renovation costs, CO_2 emissions and increasing lifespan
- ✓ Enables mass configuration, adaptation, and lifetime monitoring of configuration usage.
- ✓ Input for continuous improvement for minimalizing the GWP
- ✓ Product quality accruement and risks mitigation
- ✓ Optimize the logistic CO_2 emissions by tracking modules
- ✓ Automated input data to reports for monitoring of sustainability impact
- ✓ Secure high quality at delivery by measuring deflection and tension of building
- ✓ Improved communication with the customer to reduce the consumption
- ✓ Visibility of sustainability performance and sustainability reports
- ✓ Help property manager to optimize energy consumption and efficiency
- ✓ Profonde analysis and management alarm functions
- ✓ Broad support for automation

This thesis focuses on utilizing remote monitoring and automated analysis for product design improvement, taking control of product life cycles, and improving sustainability and digitalization. Adapteo, like most other modern companies is responsible in front of their investors to explain how Adapteo makes conscious decisions, monitors audits, and engages in sustainability. It is also strengthening Adapteo’s brand positioning Adapteo in the market as a leader in digitalization and sustainability. It will also contribute to an increased quality perception and improve Systematic Product Design and allows the use of DFSS tools and follow the DfD/A principles.

4.2 Selection of KPIs

In chapter 3.4 the CWP in the system boundaries B, C and D phases was not calculated (see Table 4). This study focuses on these phases of the Life Cycle Assessment.

Table 4 LCA-stages according to EN15978 (buildings) and EN15804 (construction materials)

System boundaries																	
A CONSTRUCTION stage					B USE stage							C END OF LIFE stage				D Benefits and loads beyond the system boundaries
Product stage			Construction process													
Raw material supply	Transport	Manufacturing	Transport	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-Recovery- Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
x	x	x	x	x	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI	LMNI

Table 5 Explanations of the secondary use LCA stages EN15804 [1]

			A4-A5	Storage of products, including the provision of heating, cooling humidity control, etc
			A4-A5	List of add construction products (additional production process to compensate for the loss of this wastage of products)
			A4-A5	Waste processing of the waste from product packaging and product wastage during the construction processes up to the end-of-waste state or disposal of final residues
		Construction process	A5	The product into the building, including manufacturer and transportation of ancillary materials and any energy of water required for installation or preparation of the construction site. It also includes the on-site operation of the product.
	B USE stage	Use	B1	Use or application of the installed products
		Maintenance	B2	Maintenance. Including provision and transport of all materials, products and related energy and water use as well as waste processing up to the end-of-waste state disposal of final residues during this part of use stages B1 to B5.
		Repair	B3	Repair (During USE stage)
		Replacement	B4	Replacement (During USE stage)
		Refurbishment	B5	Refurbishment (During USE stage)
		Operational energy use	B6	Operational energy use (e.g., operation of heating system and other building related installed services)
		Operational water use	B7	Operational water use. This information modules include provision and transport of all materials products as well as energy and water provisions, waste processing up to the end-of -waste state or disposal of final residues during this part of the usage stage.
	C END OF LIFE stage	Deconstruction, demolition	C1	Deconstruction demolition
		Transport	C2	Transport to waste processing
		Waste processing	C3	Waste processing for reuse recovery and or recycling, including provision and all transport provision of all materials products and related energy and water use
		Disposal	C4	Disposal

	D Benefits and loads from reuse	Reuse-Recovery-Recycling potential	D	Module D includes reuse, recovery and or recycling potentials, expressed as net impacts and benefits

Table 5 contains an extract from the standard of the stages that we discuss here. **Module D** is reuse/recovery/recycling potential evaluated as net impacts and benefits are calculated according to EN15804 + A2 point 6 The applicable formula for the calculation of the loads and benefits beyond the system boundary per unit of output for module D calculated for each output flow leaving the system boundary is the following:

$$e_{module\ D} = e_{module\ D1} + e_{module\ D2} + e_{module\ D3} + e_{module\ D4}$$

Figure 18 D module formula according to EN15804 + A2 point 6.4.3.3. [1]

MATERIALS

Information on the volume of materials is readable and accessible for all stakeholders in accessible projects or digital twins. The volumes and specifications can be easily generated from the products' CAD/CAM projects.

$$\boldsymbol{e_{module\ D1}}\ \textit{being the loads and benefits related to the export of secondary}\ \boldsymbol{materials}$$

$$e_{module\ D1} = \sum_i (M_{MR\ out}|_i - M_{MR\ in}|_i) \times (E_{MR\ after\ EoW\ out}|_i - E_{MR\ in}|_i \frac{Q_{R\ out}}{Q_{Sub}}\Big|_i)$$

Figure 19 D1 module formula according to EN15804 + A2 point 6. [1]

$M_{MR\ out}$ - **Amount of material** existing in the system that will be recovered (recycled or reused) in a subsequent system. This amount is determined at end-of-waste point and is therefore equal do output flow of "materials to recycling (kg)" reported for modules A4, A5, B and C [1]

$M_{MR\ in}$ - **Amount of input material** to the product system that has been removed (**recycle or reuse)** from a previous system (determine at the system boundary)

$E_{MR\ after\ EoW\ out}$ - Specific emissions and resources consumed per unit to finalize arising from material recovery recycling and reusing processes of the subsequent system after the end-of-waste state [1]

$E_{MR\ after\ EoW\ in}$ - Specific emission and resources consumed per unit of finalizes arising from material recovery (recycling and reusing) processes of the previous system after the end-of-waste stage [1]

Q_{Rout} / Q_{sub} - QUALITY ratio between outgoing recovered material (recycled and reuse) and the substitute material [1]

QUALITY – Healthy house

The health of a wooden construction depends on the thickness of the insulation. Unfavorable conditions happen at the minimum limits: if either insulation is pushed to be as thin as possible or ventilation and heating is used as little as possible. Wood is very sensitive to usage and design errors. The most damage to wood occurs due to mold and fungi caused rotting. Which can be avoided by smart use and competent design. This can be achived with monitoring the use and applying the gathered data. The most important parameter for mold growth is humidity: if the humidity is over 75% there is a danger of a wood decaying mold or fungi growth.

Critical conditions for mold growth

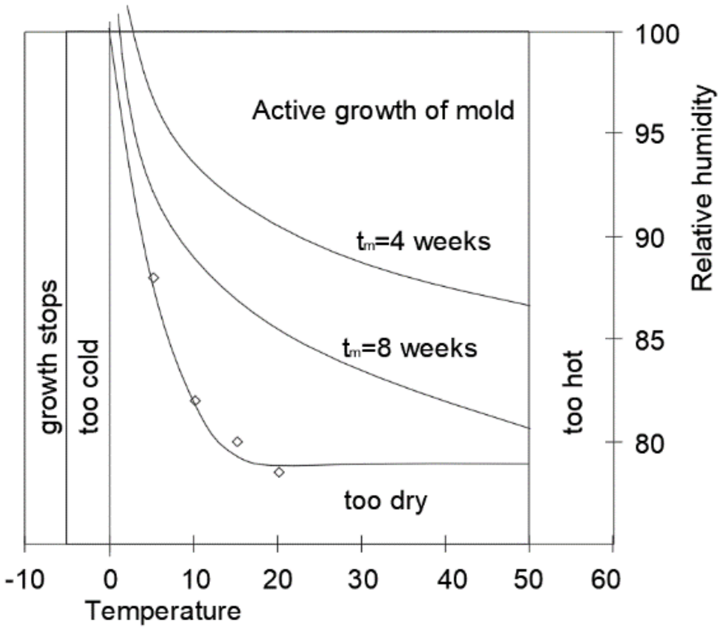

Figure 20 Diagram of suitable environment for growth conditions of biological particles [40]

Microbiological growth suitable conditions (Figure 20):

1. Humidity (relative humidity on the growing area ≥ 75...80 %).
2. Temperature (0...+50°C, but the best temperature for development is +20...+35°C);
3. Time of occurrence of suitable growth conditions.
4. Growing medium (enough nutrients, alkalinity pH 5...6).

Water vapor condensation

Another important factor contributing to the health of a construction is the condensation of water vapor, which can cause the wood to degrade and the metal construction to corrode.

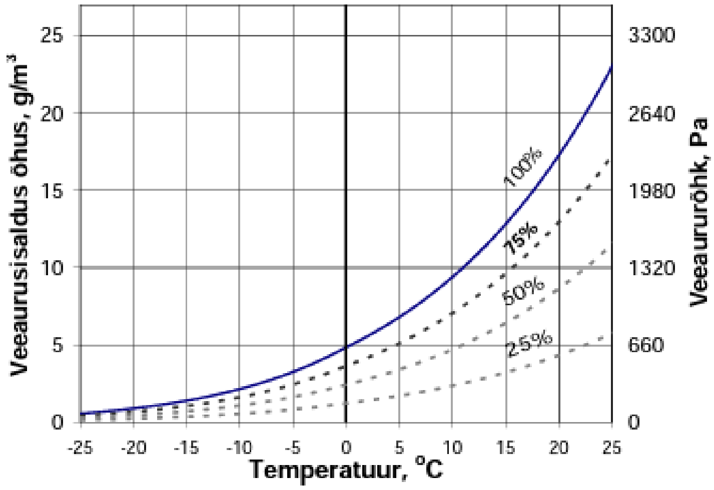

Figure 21 Diagram of an environment suitable for condensation [39]

Favorable conditions for construction materials are achived with added insulation and better ventilation and heating which in turn means higher expenses and CO_2 emissions. To find the most energy effcient balance between isolation and HVAC solutions accurate data must be gathered and applied to optimize the designing as well as indoor climate controlling during use.

Defining of the KPIs of Structural health monitoring (SHM) ensure the **QUALITY of MATERIAL**

KPIs in physical measurements:

Table 6 KPIs of physical measurements

KPI			Description and what it measures
SMART PRODUCT	PHYSICAL MEASUREMENTS	HUMIDITY	Inside the module, to measure the environment, to prevent damage Inside the rooms and air quality
		TEMPERATURE	Inside the module, to measure the environment, To prevent damage Inside the rooms
		TEMPERATURE in WALL	To prevent damage Inside the structure
		VOC	Volatile organic compounds (VOCs) are organic compounds that have a high vapor pressure at room temperature.
		INDOOR VENTILATION	CO2 monitoring to ensure air quality
		AIRTIGHTNESS	To prevent air leaking and air moving inside the construction
		WEATHER DATA	For comparing and analyzing the consumption and rooms, construction temperature and humidity (Day, Month, year, AM, PM)

		NATURAL LIGHT	Analyzing and reducing the consumption of lightening, Sensing Outdoor light level
		NATURAL VENTILATION	Compare and predict added air flows that are not accounted for in ventilation calculations, Sensing Outdoor air flow
		DIFFUSION	Control of moisture permeability and thermal conductivity of the wall Diffusion occurs between the inner surface and the outer surface due to pressure differences.
		CONVECTION	Control of wall air density and actual thermal conductivity If the air moves in uncontrollable bursts, it is called convection. This can happen on the exterior if there are joints in the vapor barrier.
		MICROBES	Bacteria, fungi, mosses, algae, beetles - identification, avoidance we need the help of scientists (mold, fungi?)

KPIs for track quantities in geometric and geographic measurements

Table 7 KPIs of geometrical and location measurements

			Description and what it measures
SMART PRODUCT	GEOMETRICAL AND LOCATION MEASUREMENTS	GEOMETRY	point gaps between module constructs, to identify, changes in dimensions and shape of modules during tram transport and lifts, subsidence and displacements
		LOCATION DIRECTION	Geographical location and direction on the weather chart, Determine an important part in energy calculations
		TENSION	wooden and metal connections to avoid breakage of metal connections, Wood belt, wood-structure work limit values
		G-FORCE	supports, lifting schemes, transport positions, wind, earthquakes, natural phenomena,
		LOCATION	Movement, storage, logistics, A place in the Digital Twin world; Location of 500+ modules in stock
		ORIENTATION	Orientation and View, The direction of the building
		SUNLIGHT TRANSMISSION OF GLASS	wear of the solar factor g of the glass part and light transmission
		LEVELLING	sinking of the module, during transport - lifting, storage, storage. If the module has sunk more than 9* degrees during transport, it must be checked

RISK mitigation KPIs to prevent material destruction

Table 8 KPIs of hazards measurements

			Description and what it measures
ALARMS	HAZARDS	FIRE	Fire prevention inside structures. In the event of a danger to the electrical wiring, the sensor will trip the fuse
		GAS	fire safety sensors are built into the modules Fire safety during storage (300+ modules!)
		SMELL	needs clarification
		ALARM SYSTEMS	Signals reach the house alarm system (ATS) Alarm and fire safety sensors transmit a signal

KPIs of Energy consumption

Table 9 KPIs of consumption

			Description and what it measures
ENERGY SAVING	CONSUMPTION/PRODUCTION	HEATING	Interaction with the smart house; preventive reheating as needed to prevent excess moisture, heating data collection for ML analysis
		COOLING	Cooling data collection for ML analysis

		VENTILATION	Interaction with the smart house; proactive regulation of ventilation, as needed to avoid excess humidity, collection of vent data for ML analysis
		LIGHTENING	
		WATER HEATING	
		WATER SUPPLY	collection of water consumption data for analysis

According to Tables 6 to 9 and based on the above, the Concept model shows the selected KPIs in the LCA stages. In module D substitution effects are calculated only for the resulting net output flow [1]. In order to monitor the long lifetime in Product Category Rules in a digital and intelligent way, both in terms of product, service, and use cases, the possible monitoring during A, B, C stages is outlined in Figure 22:

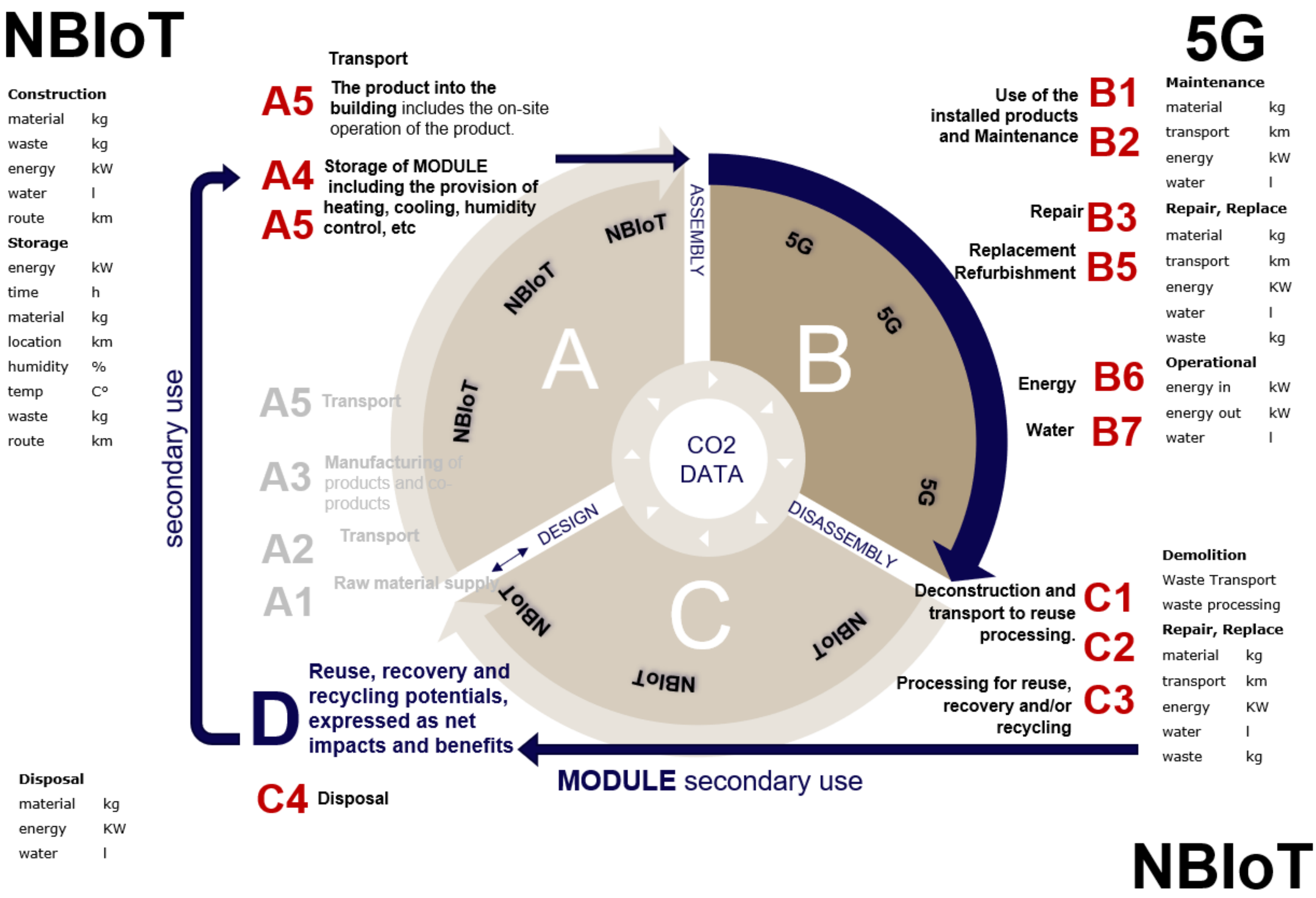

Figure 22 Extended IoT concept from LCA with a list of monitored measurements and units.

4.3 Test case of data monitoring - Process Modelling

Test case focusing on the quality of the material by Structural Health Monitoring (SHM) to achieve the Healthy building. According to the module's service life, the important sensors help prevent material damage and maintain the health of the building. Protecting the wood of the structure is crucial in extending the life of the building monitoring the humidity, the temperature and the time of these conditions. These unsuitable conditions can easily occur during the transport and storage phases. Weather conditions, packaging damages, poor storage options, small animals and birds, delays in work processes on the construction site, incorrect planning, and other conditions can create unexpected and unfavorable situations for the product.

In the mobile product phase, the environment inside the modules is also periodically monitored during storage. The storage instructions stipulate the periodicity of control operations and the exact measurement locations and reference sizes. The procedure is time-consuming and requires human labor, the price of which increases and the availability decreases. It takes an average of 30 minutes to measure one module in the package, plus the time of driving to the warehouse and fuel. In Figure 23 pictures of the process of current humidity measurement is shown. The larger warehouses have 300 to 500 modules that must be checked every three months. In the summertime, at least once per month. During each control measurement, the module packaging film is cut and re-taped. This increases the tearing of the packaging during transport.

1. Take a photo of the Module Serial Number
2. Take a safe ladder and check its stability:
3. Mount the measuring device according to the user manual of the measuring device:

4. Take a picture of the result:
5. Take measurements from different places:
6. In the case of a higher-than-permitted reading, take a picture where the result is within the norm.

7. Take pictures of each outer corner in the same order as the inner measurement.

Figure 23 The current procedure of moisture measuring in storage stage A4-A5

From IVL's LCA report, it is known that the largest CO_2 emissions come from the production of construction materials and the energy consumption of buildings. One of the biggest CO_2 generators among building materials is insulation. CO_2 reduction targets force designers to mediate insulation to calculated minimums in wall U-values and thickness to minimize CO_2 emissions from materials. On the other hand, in order to save energy consumption, the situation where, in the absence of people, reducing the work of the indoor climate in the room creates a favorable environment for wood damage to occur inside the structure of the building may arise.

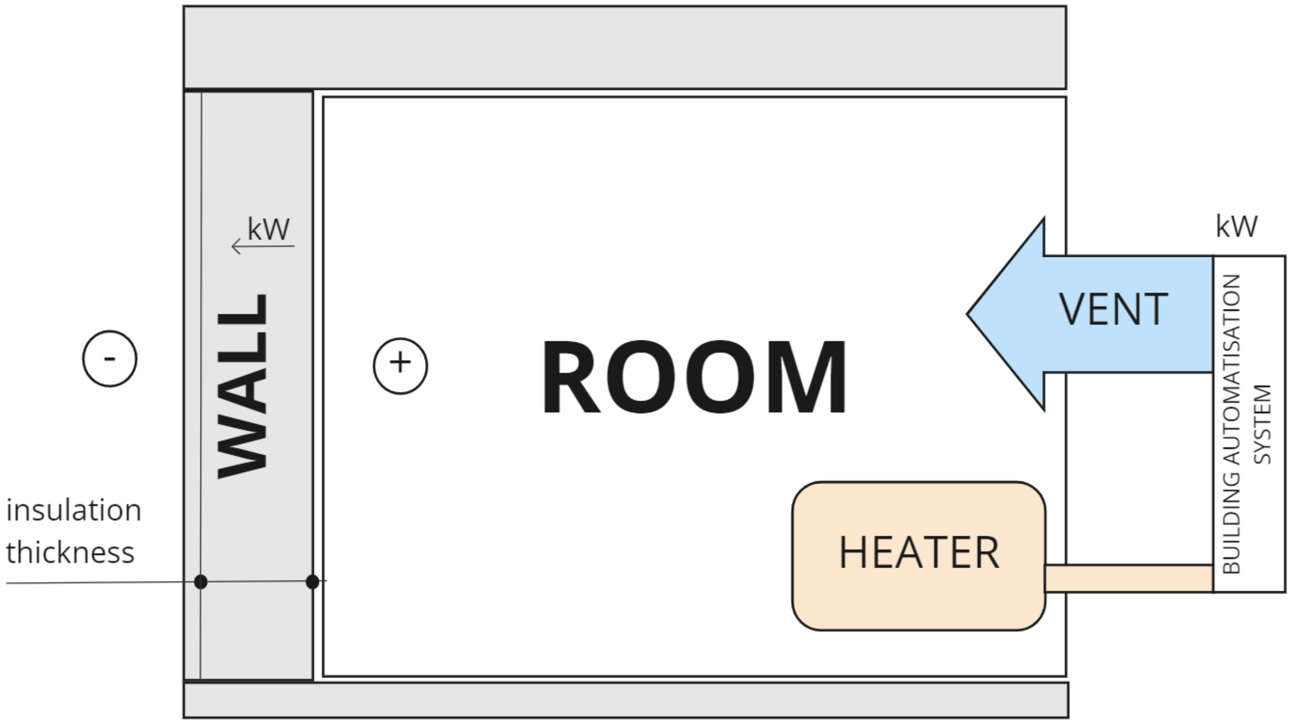

Figure 24 Defining the TEST system boundary

For an optimal system a balance point between the thermal insulation layer thickness and the energy used to create indoor climate must be found. To balance this system data is needed as an input for design improvements and automatic system management. The test system boundary is shown in Figure 24. Stored and archived data creates a Big Data database enabling machine learning and intelligent balanced systems in the future. All data collection must follow the functional unit (a module), calculation principles, and data quality requirements defined in the LCA. The development of the home system is a long-term process and will be developed gradually, starting from the biggest polluters like insulation, metal construction, and energy used for indoor climate control. The IoT Concept for the Life Cycle Assessment of Modular Wooden Houses will follow all earlier mentioned requirements as well as construction product regulations, Ecodesign regulations, construction design regulations and environment regulations established in the European Union.

Test case monitoring system examines chosen rooms in chosen modules. Data is collected on the weather, the module's indoor climate and the temperature and humidity of the wall construction. The purpose of the test monitoring is to test the complexity of the data collection, the format of the obtained data, the compatibility of the data with previously used data and the evaluation of the readings.

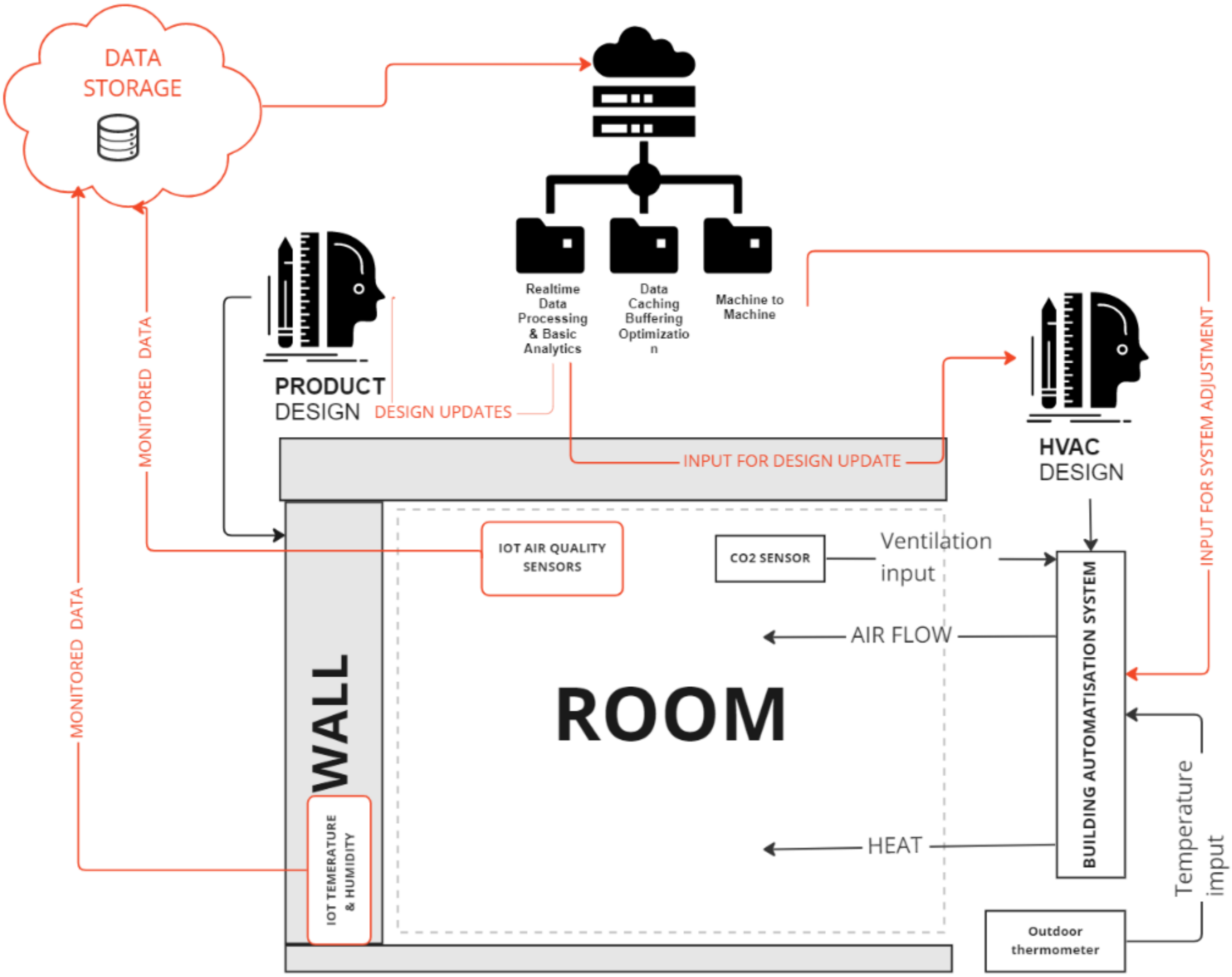

Figure 25 Specifying the functional requirements

NBIoT sensors for temperature and humidity are installed inside the structure (wall) or on the surface. The indoor climate sensors are installed on the surface of the finished wall of the room. The data is stored in the cloud-based data warehouse of the service provider. See Figure 25. The stored data is used in comparison tables and graphs at the observed time and time period. The graphs are marked with reference values that serve as a guide for determining deviations. When analyzing the data, the stage of the project is determined, such as: installation, construction of interior works, construction of the facade, installation of the roof, building connected to technical systems, etc. The length of the test period is determined by the battery life of the test IoT sensors. The IoT monitoring system is described in Figure 26.

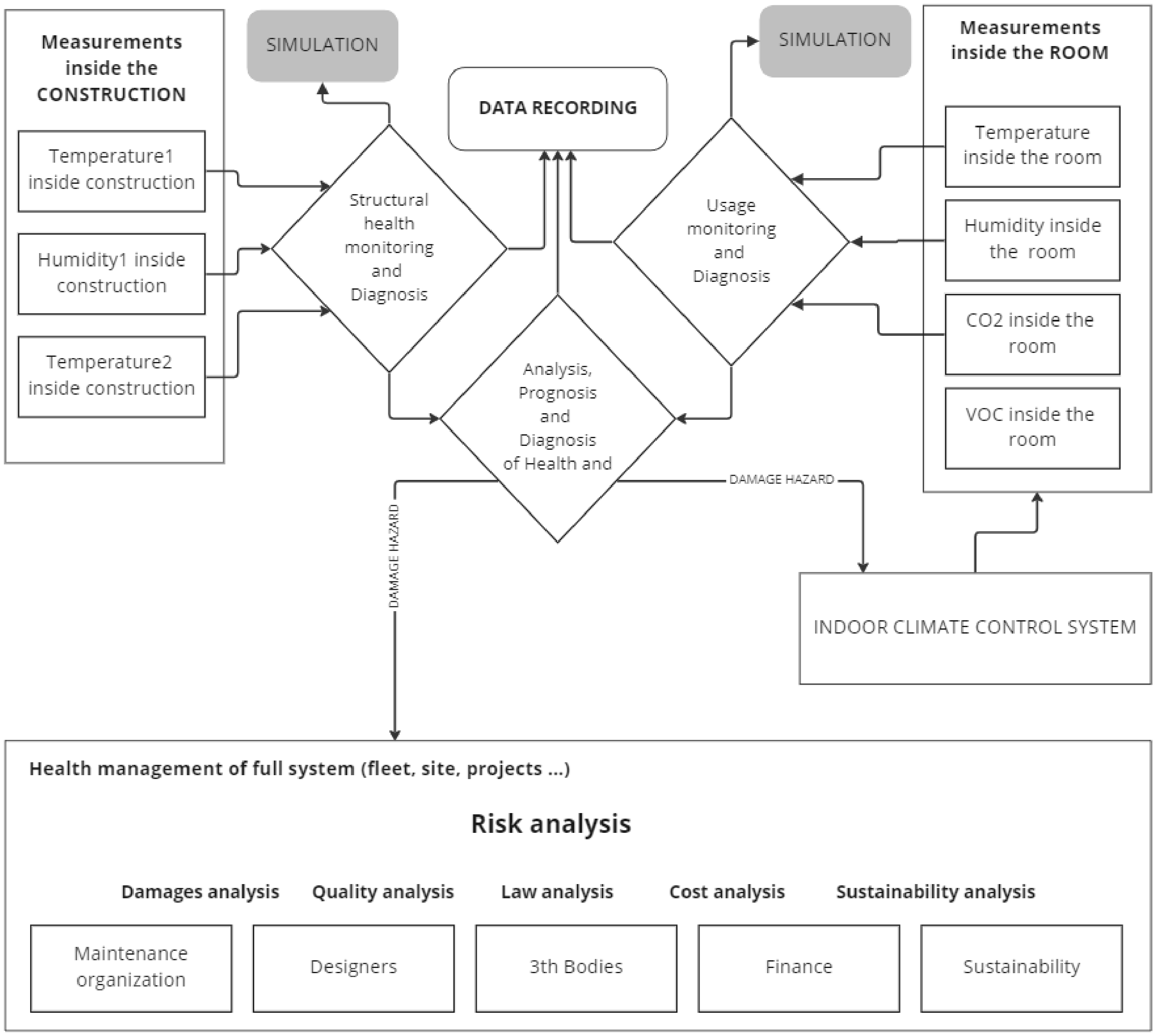

Figure 26 IoT monitoring in Structural Health Monitoring system

Test case Pilot Project is two-story daycare in Rovaniemi. The project is based in a new development product series developed for Finland's daycares and school field. In this work, the installation and location plans are prepared with AutoCAD software, where the types of sensors and the planned locations will be specified. The choice of sensors will be made based on the "healthy house" principles described above. Based on the knowledge of construction physics, the greatest risk of temperature drops and, therefore, moisture formation is in the corners of the building structure and the steel construction as cold bridge inside the wall. Based on this, sensors measuring the temperature and humidity inside the wall are installed near the metal posts in the corners of the modules. Existing devices do not have the capability of working in two different mobile communication systems (5G and NB-IoT) and being flexibly expandable to add sensors. Therefore, the test is done with different existing devices and sensors in the Rovaniemi study case to get some data and see the problems and shortages in technology and data collection process. Figure 27 shows the location of the sensors.

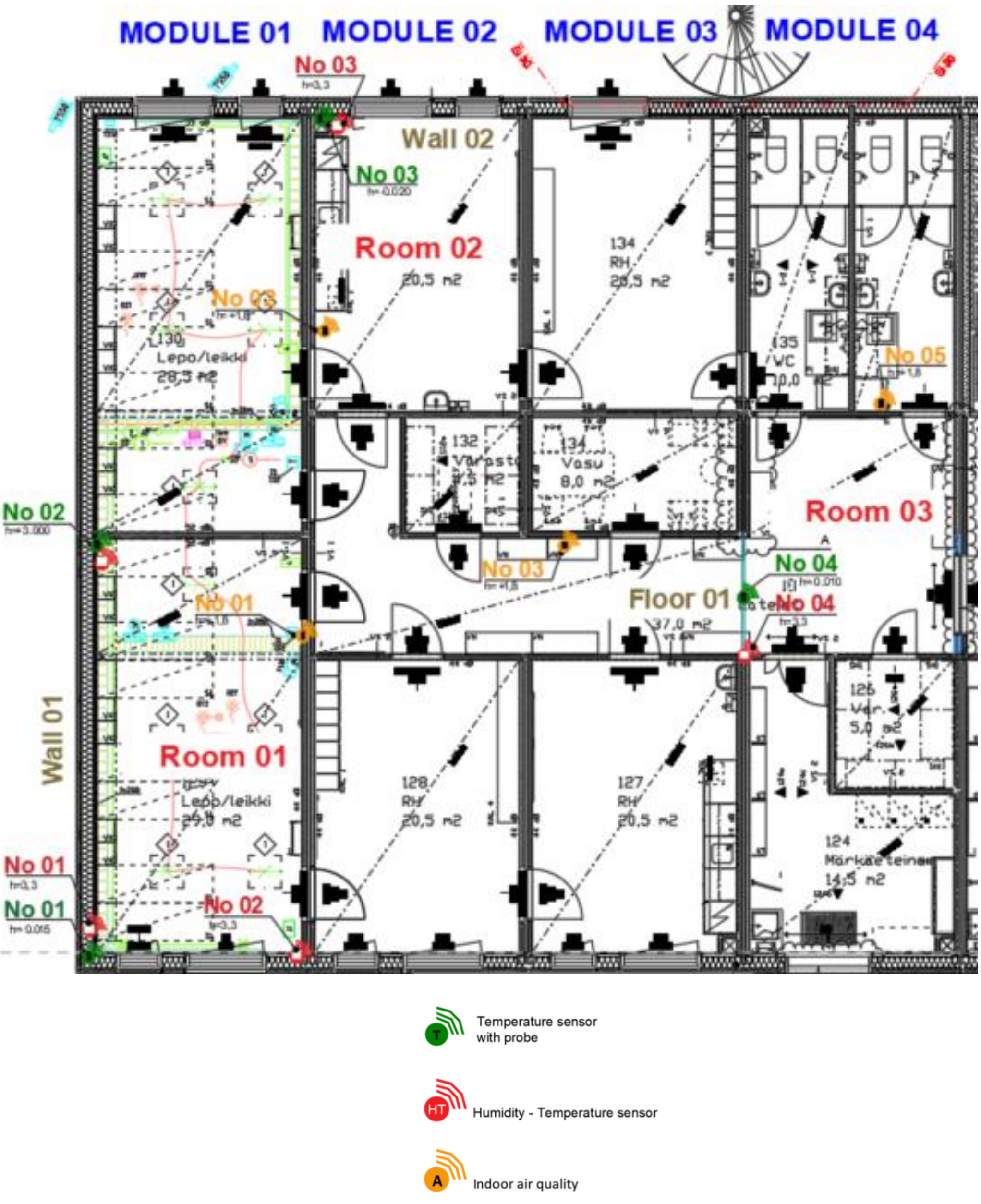

Figure 27 Location of the sensors on the first floor

4.4 Data collection preparing

SELECTION OF SENSORS

The test is performed on a cloud-based product monitoring solution. The equipment is standard, and the Test is solved on the existing Telia platform. A different number of temperature and humidity sensors are used for each module, a standard indoor air quality sensor is used to determine the overall quality of the room. All acquired sensors are IoT-based, which differs from the initially planned solution (Figure 28).

The test case includes the following components:

- Devices
- Connectivity
- APIs (Open Standard)
- Data processing
- Data storage

Monitoring devices include integrated sensors such as temperature and humidity, etc. Devices have Nordic, EU/EEA, and global coverage capabilities, and Devices based on rechargeable batteries or replaceable batteries. Devices will use modern and appropriate mobile network technology NB-IoT.

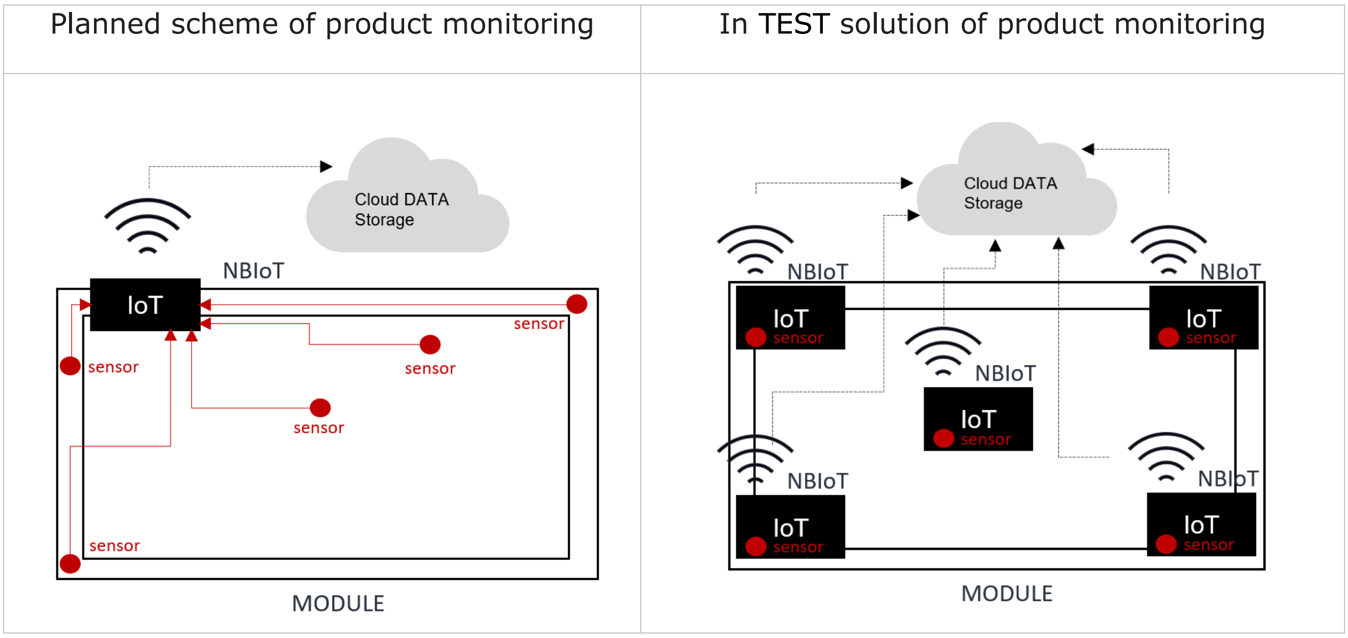

Figure 28 Planned and test schemes of the IoT devices connectivity

Selected sensors are NB-IoT sensors with low power consumption for temperature, humidity and air quality in Table 10.

SENSORS CHARACTERISTICS

Table 10 Sensors technical description

Cellular	NB-IoT band: 1, 2, 3, 4, 5, 8, 12, 13,17, 18, 19, 20, 25, 28, 66 3GPP: Release 13
Battery	6300 mAh replaceable 3xAA batteries
Dimensions & weight	H:124, D:28, W:60 (mm), 110g incl. batteries Enclosure: plastic ABS, color white, IP30
Operating	Temperature: -35 °C to +70 °C, Humidity: 0 to 100% RH, Temperature sensors, two options for cable length: 1m or 5m
Accuracy	Temperature: ±0.2 °C (typical) Humidity: ±2.0 %RH (typical)
SIM	Surface-mounted M2M SIM component (MFF2 size standard). Not changeable by the user
Memory size	40 000 measurements
Measurement interval	Standard configuration: 15 min measurement interval, 60 min data transmission interval. Can be re-configured based on the customer use case.

PLATFORM SELECTION

The Data can be accessed through standard APIs, which enable integration to third-party systems and REST-compliant (Representational State Transfer) standards in the development of APIs. In the project will be used the **Telia IoT platform** [40] (screenshot in Figure 29)

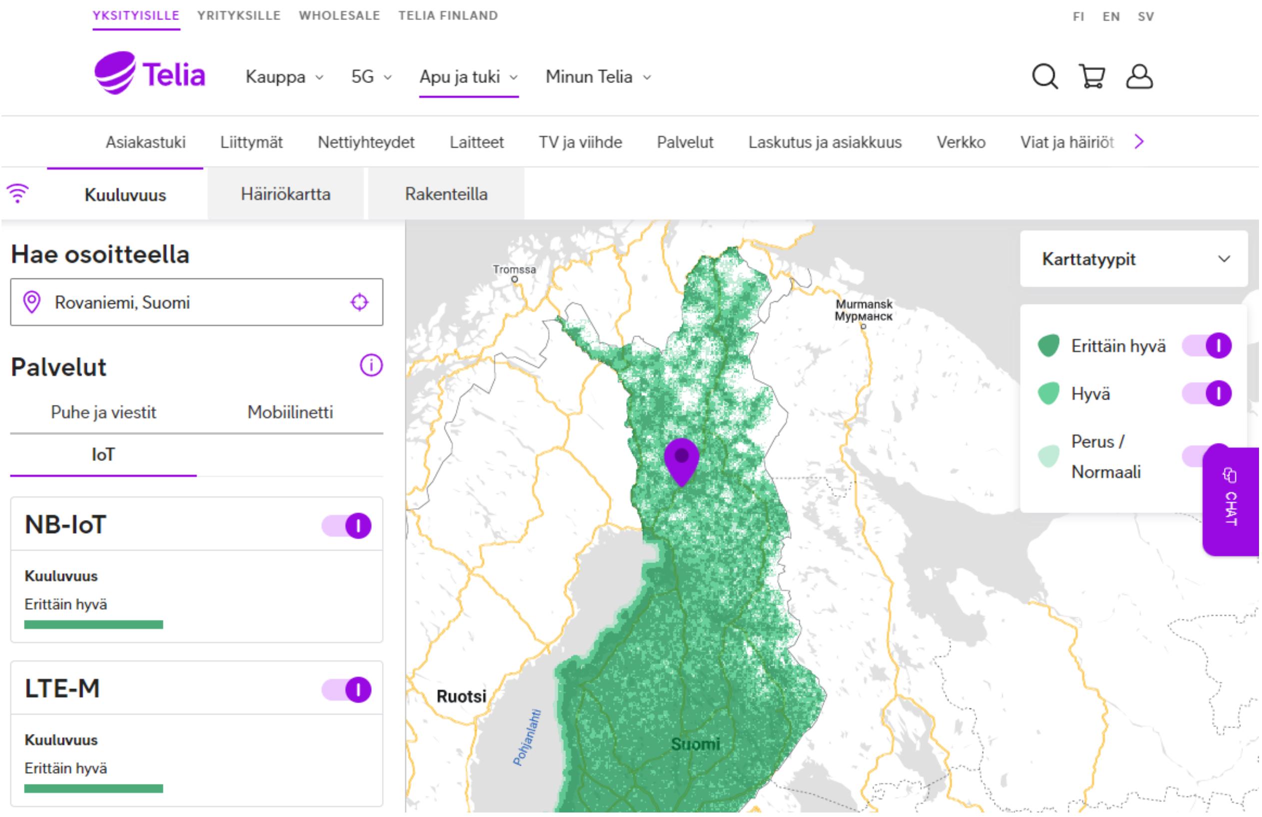

Figure 29 Telia IoT coverage map [41]

INSTALLATION OF SENSORS

The installation of the sensors began with the numbering of the sensors and their transfer to the building plans, following the previously prepared location diagrams. The protective cover is removed, and the sensor is switched on by watching the indicator light flash until the light turns green. Sensors are taped to the surface of the construction (see Figure 28). Temperature sensors designed to measure temperature and humidity inside the wall are taped to the metal structure inside the wall.

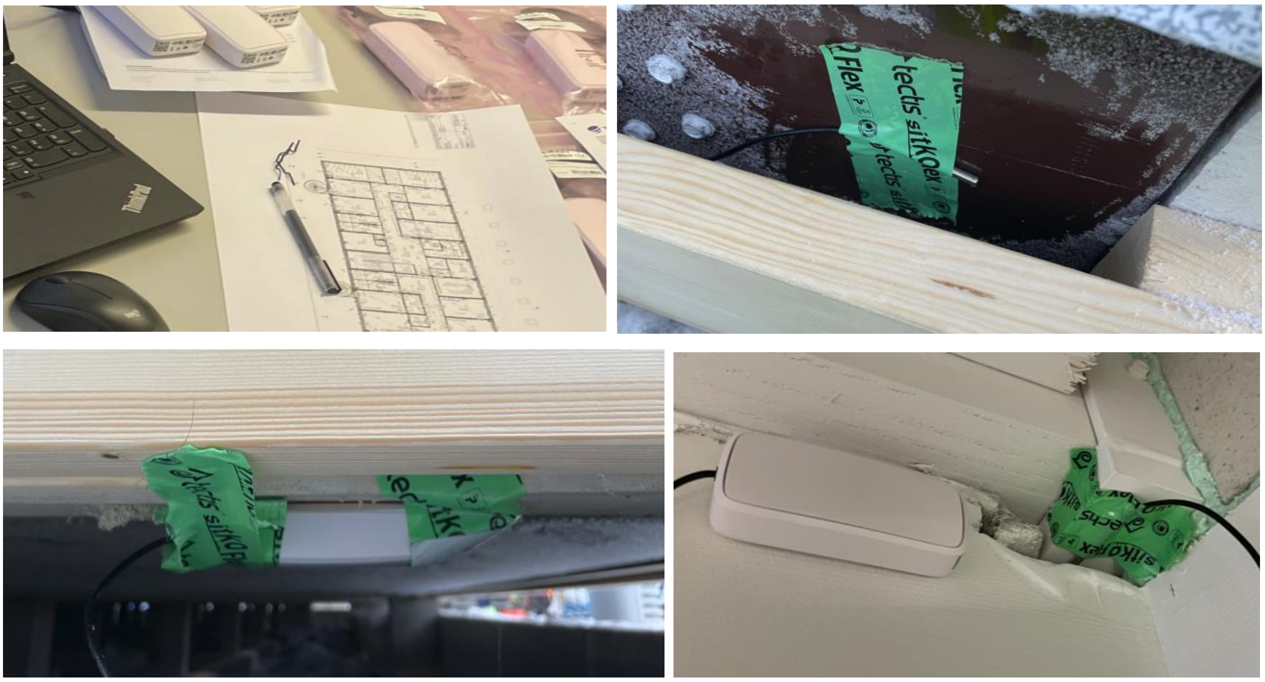

Figure 30 Photos of sensor installation

The sensor IoT device housing is attached to the bottom of the building in an accessible place. The measuring probe for the sensors behind the suspended ceilings is taped between the wall construction, and the IoT device of air quality is taped on the in-room wall (Figure 30). During the installation of sensors, the sensors were numbered, the sensor numbers were marked on the plan, and a picture of the location was taken. The indoor room monitoring sensors are mounted on top of wall surface.

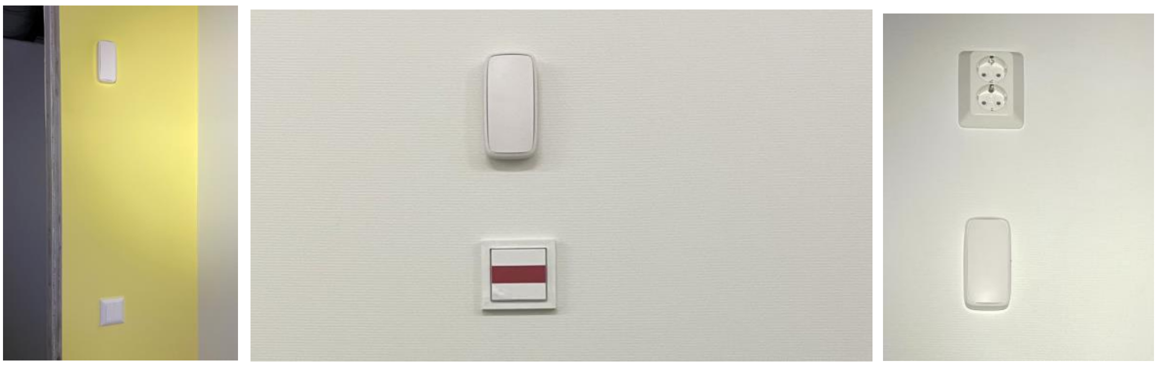

Figure 31 Photos of sensor installation

Specification of the sensors:

Table 11 List of sensors with sensors serial numbers.

MODULE No	ROOM No	Wall No	Sensor Pos	floor	type	SN
MODULE 01	Room 01	Wall 01	Temp 01	1st floor	indoor temp 1m probe	282C02411B44
MODULE 01	Room 01	Wall 01	Temp 02	1st floor	indoor temp 1m probe	282C02411B46
MODULE 02	Room 02	Wall 02	Temp 03	1st floor	indoor temp 1m probe	282C02411ADF
MODULE 03	Room 03	Wall 04	Temp 04	1st floor	indoor temp 1m probe	282C02411AE5
MODULE 05	Room 05	Wall 03	Temp 05	1st floor	indoor temp 1m probe	282C02411AE6
MODULE 06	Room 04	Wall 04	Temp 06	1st floor	indoor temp 1m probe	282C02411AFD
MODULE 11	Room 06	Wall 05	Temp 07	2nd floor	indoor temp 1m probe	282C02411AFE
MODULE 14	Room 07	Wall 06	Temp 08	2nd floor	indoor temp 1m probe	282C02411AFF
MODULE 11	Room 06	Wall 05	Temp 09	2nd floor	indoor temp 1m probe	282C02411B00
MODULE 01	Room 01	-	AQ 01	1st floor	indoor air quality	282C02411580
MODULE 02	Room 02	-	AQ 02	1st floor	indoor air quality	282C02411581
MODULE 03	Room 03	-	AQ 03	1st floor	indoor air quality	282C02411582
MODULE 05	Room 05	-	AQ 04	1st floor	indoor air quality	282C02411583
MODULE 04	Room 03	-	AQ 05	1st floor	indoor air quality	282C02411584
MODULE 06	Room 04	-	AQ 06	1st floor	indoor air quality	282C02411585
MODULE 11	Room 06	-	AQ 07	2nd floor	indoor air quality	282C02411586
MODULE 14	Room 07	-	AQ 08	2nd floor	indoor air quality	282C02411587
MODULE 18	Room 08	-	AQ 09	2nd floor	indoor air quality	282C02411588
MODULE 16	Room 04	-	AQ 10	2nd floor	indoor air quality	282C02411589
MODULE 01	Room 01	Wall 01	Temp/HUM 01	1st floor	temp/humidity	282C02407889
MODULE 01	Room 01	Wall 01	Temp/HUM 02	1st floor	temp/humidity	282C0240788A
MODULE 02	Room 02	Wall 02	Temp/HUM 03	1st floor	temp/humidity	282C0240788B
MODULE 03	Room 03	Wall 04	Temp/HUM 04	1st floor	temp/humidity	282C0240788C
MODULE 05	Room 05	Wall 03	Temp/HUM 05	1st floor	temp/humidity	282C0240788D
MODULE 06	Room 04	Wall 04	Temp/HUM 06	1st floor	temp/humidity	282C0240788E
MODULE 11	Room 06	Wall 05	Temp/HUM 07	2nd floor	temp/humidity	282C0240788F
MODULE 14	Room 07	Wall 06	Temp/HUM 08	2nd floor	temp/humidity	282C02407890
MODULE 11	Room 06	Wall 05	Temp/HUM 09	2nd floor	temp/humidity	282C02407891

DATA COLLECTION SHEET

According to EN ISO 140044, the first step of data collection is the design of the Data collection sheet (Figure 30). Data collection is required to validate and relate data to the functional unit. After the completed inventory, it is necessary to check its compliance with the system boundary and, if necessary, change the data collection sheets.

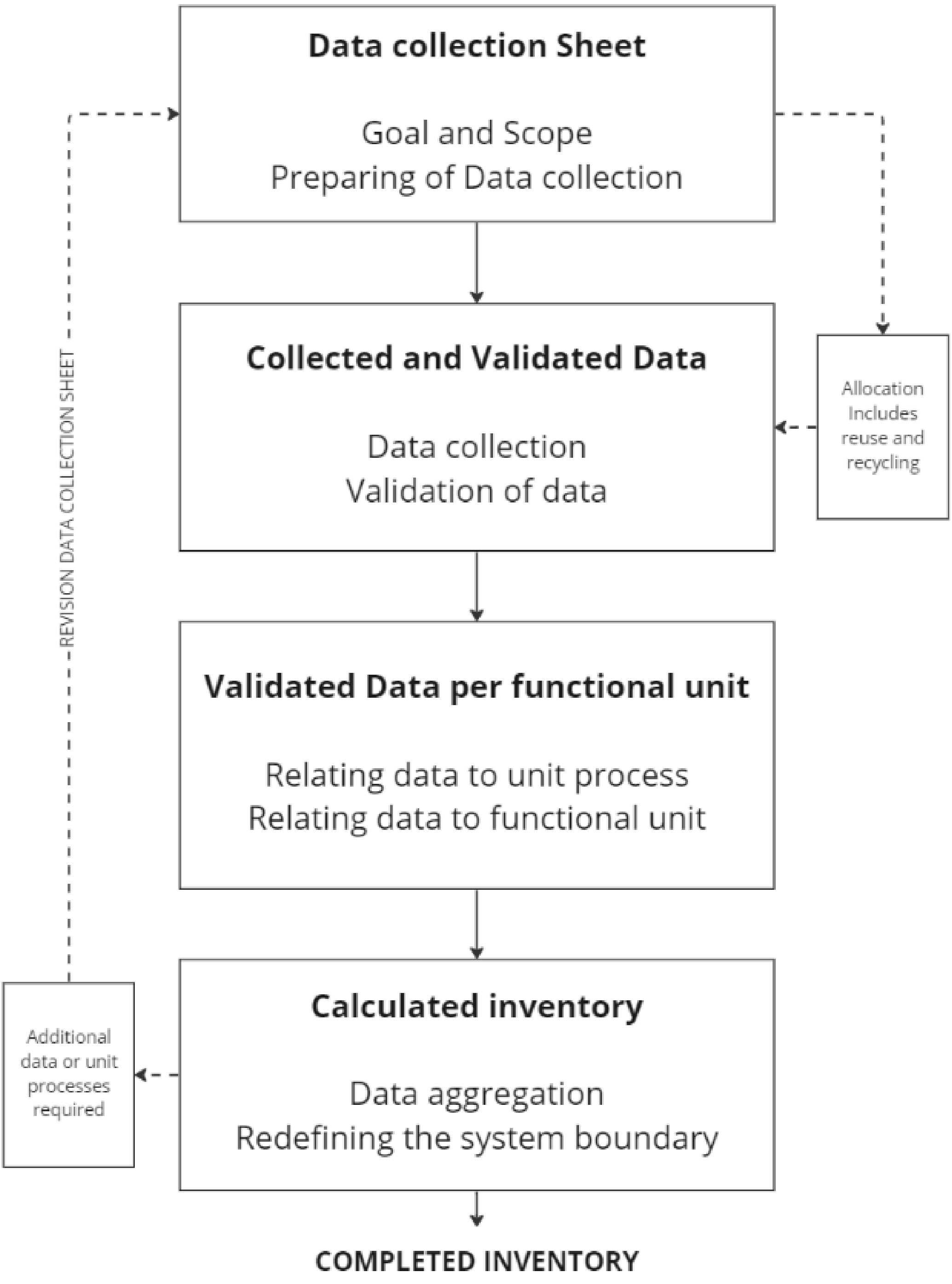

Figure 32 Data collection process [24]

The data collection sheet (Figure 32) is designed in excel. On Figure 34 is shown in colors the sensor’s locations in the room. The data collection sheets are supported by AutoCAD 2D drawings of the modules plans and sensor’s locations. The colors of the headings are the same as the sensor or component on the 2D drawing (Figure 35). Full data sheet template is appendix 02.

	A	B	C	D	E	F	G	H	I	J	K	L
1	December 2022	Wall 01						Room 01				
2		TEMP 1m probe		TEMP/HUM				indoor air quality				
3		No 01	No 02	No 01		No 02		No 01				
4		282C02411B44	282C02411B46	282C02407889		282C0240788A		282C02411580				
5		TEMP	TEMP	TEMP	HUM	TEMP	HUM	TEMP	HUMIDITY	SAQI		
6	Reference	>15°	>16°	>15°	<75%	>18°	<70%	22°	25-45%	100		
7	Goal and Scope	mould/ condensation	mould/ condensation	mould/ condensation	mould/ condensation	mould/ condensation	mould/ condensation	human	human	human		
8	Date	Temp 01	Temp 02	Temp/HUM 01| °C	Temp/HUM 01 | %	Temp/HUM 02| °C	Temp/HUM 02| %	AQ TEMP 01 | °C	AQ 01 | %	AQ |	Date	control
9	2022-12-06 00:00:00	-0.4	8.4	-0.7	93.9	8.7	47.0	8.4	48.0	171.0	2022-12-06 00:00:00	0
10	2022-12-06 01:00:00	-0.3	8.6	-0.9	92.0	8.7	47.1	8.6	48.0	178.8	2022-12-06 01:00:00	0
11	2022-12-06 02:00:00	-0.3	8.7	-1.1	92.0	8.9	47.0	8.9	47.0	186.3	2022-12-06 02:00:00	0
12	2022-12-06 03:00:00	-0.2	8.9	-1.2	91.8	9.0	47.3	9.1	47.0	190.3	2022-12-06 03:00:00	0
13	2022-12-06 04:00:00	-0.2	9.0	-1.2	91.0	9.1	48.0	9.3	47.0	195.3	2022-12-06 04:00:00	0
14	2022-12-06 05:00:00	-0.1	9.1	-1.2	91.0	9.1	48.0	9.5	46.5	197.5	2022-12-06 05:00:00	0
15	2022-12-06 06:00:00	-0.1	9.2	-1.0	91.0	9.0	49.2	9.5	47.5	176.8	2022-12-06 06:00:00	0
16	2022-12-06 07:00:00	0.0	9.2	-1.0	91.0	9.0	50.9	9.4	49.0	163.5	2022-12-06 07:00:00	0
17	2022-12-06 08:00:00	0.1	9.3	-1.0	91.3	8.9	51.5	9.4	50.3	159.0	2022-12-06 08:00:00	0

Figure 33 Data collection sheet.

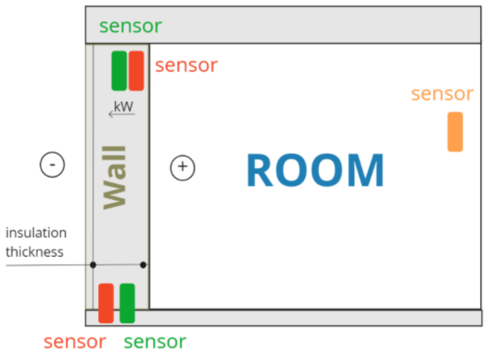

Figure 34 Scheme’s color guidance. The grey area is the wall, and the white area is the room.

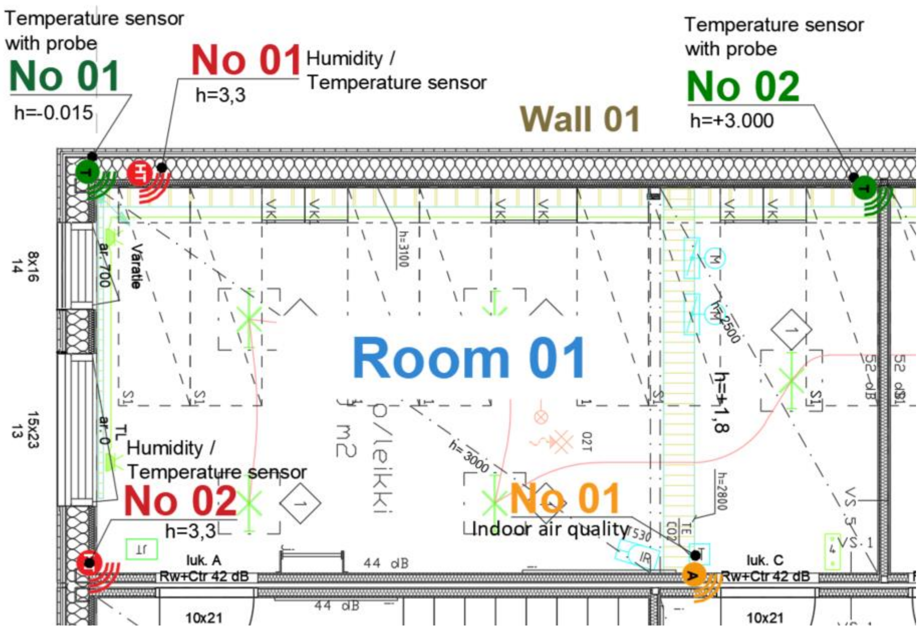

Figure 35 Room 01 sensor location scheme

4.5 Real-time Monitoring and Visualization

Analyzed Data was recorded on the Telia platform every hour. Recorded Data is downloaded in excel format, and all testing analyses are made in excel (Figure 36). Room 01 was monitored for ten days, 6.12 – 16. 12.22. On the data report from 16.12.22, there is a recording time error on 06.12.22 at 10 o'clock. All time spots where reading was missing were removed from the list.

8	Date	Temp 01	Temp 02	Temp/HUM 01| °C	Temp/HUM 01 | %	Temp/HUM 02| °C	Temp/HUM 02| %	AQ TEMP 01 | °C	Air quality 01 | %	Air Quality |	Date	control	Date	control
9	2022-12-06 00:00:00	-0.35	8.375	-0.711111111	93.88888889	8.694444444	47	8.4	48	171	2022-12-06 00:00:00	0	2022-12-06 00:00:00	0
10	2022-12-06 01:00:00	-0.3	8.55	-0.9	92	8.744444444	47.05555556	8.625	48	178.75	2022-12-06 01:00:00	0	2022-12-06 01:00:00	0
11	2022-12-06 02:00:00	-0.3	8.725	-1.05	92	8.85	47	8.85	47	186.25	2022-12-06 02:00:00	0	2022-12-06 02:00:00	0
12	2022-12-06 03:00:00	-0.225	8.85	-1.161111111	91.83333333	8.955555556	47.33333333	9.05	47	190.25	2022-12-06 03:00:00	0	2022-12-06 03:00:00	0
13	2022-12-06 04:00:00	-0.175	8.975	-1.2	91	9.05	48	9.3	47	195.25	2022-12-06 04:00:00	0	2022-12-06 04:00:00	0
14	2022-12-06 05:00:00	-0.1	9.1	-1.15	91	9.122222222	48	9.475	46.5	197.5	2022-12-06 05:00:00	0	2022-12-06 05:00:00	0
15	2022-12-06 06:00:00	-0.1	9.175	-1.022222222	91	9.022222222	49.16666667	9.475	47.5	176.75	2022-12-06 06:00:00	0	2022-12-06 06:00:00	0
16	2022-12-06 07:00:00	-0.025	9.225	-0.977777778	91	8.983333333	50.88888889	9.4	49	163.5	2022-12-06 07:00:00	0	2022-12-06 07:00:00	0
17	2022-12-06 08:00:00	0.075	9.275	-0.966666667	91.27777778	8.938888889	51.5	9.4	50.25	159	2022-12-06 08:00:00	0	2022-12-06 08:00:00	0
18	2022-12-06 09:00:00	0.1	9.3	-0.9	91.94444444	8.966666667	52.66666667	9.4	51	161.5	2022-12-06 09:00:00	0	2022-12-06 09:00:00	0
19	2022-12-06 11:00:00	0.15	9.375	-0.9	91.22222222	9	54.16666667			160.6666667	2022-12-06 10:00:00	0.04167	2022-12-06 10:00:00	0.04167
20	2022-12-06 12:00:00	0.225	9.4	-0.861111111	91.72222222	9	54.22222222	9.6	52.66666667	147.25	2022-12-06 11:00:00	0.04167	2022-12-06 11:00:00	0.04167
21	2022-12-06 13:00:00	0.3	9.475	-0.805555556	91.05555556	9.088888889	55	9.75	53	160.75	2022-12-06 12:00:00	0.04167	2022-12-06 12:00:00	0.04167
22	2022-12-06 14:00:00	0.3	9.625	-0.861111111	90	9.211111111	55	9.8	52.75	174	2022-12-06 13:00:00	0.04167	2022-12-06 13:00:00	0.04167
23	2022-12-06 15:00:00	0.3	9.8	-1.144444444	88.33333333	9.633333333	54.22222222	10.25	51.5	174	2022-12-06 14:00:00	0.04167	2022-12-06 14:00:00	0.04167
24	2022-12-06 16:00:00	0.3	10.025	-1.127777778	88.11111111	10.23888889	53.27777778	10.65	51	168.5	2022-12-06 15:00:00	0.04167	2022-12-06 15:00:00	0.04167
25	2022-12-06 17:00:00	0.3	10.225	-1.094444444	87.55555556	10.51111111	51.61111111	11	50	158.5	2022-12-06 16:00:00	0.04167	2022-12-06 16:00:00	0.04167
26	2022-12-06 18:00:00	0.35	10.45	-1.111111111	87	10.22777778	51.16666667	11.05	48.75	148.75	2022-12-06 17:00:00	0.04167	2022-12-06 17:00:00	0.04167
27	2022-12-06 19:00:00	0.35	10.675	-1.083333333	87.05555556	10.26111111	50.38888889	11.175	47.75	143	2022-12-06 18:00:00	0.04167	2022-12-06 18:00:00	0.04167
28	2022-12-06 20:00:00	0.4	10.825	-1.177777778	85.22222222	10.43333333	49.44444444	11.325	46.75	140	2022-12-06 19:00:00	0.04167	2022-12-06 19:00:00	0.04167
29	2022-12-06 21:00:00		11.025	-1.25	84.61111111	10.60555556	48.38888889	11.5	45.75	139	2022-12-06 20:00:00	0.04167	2022-12-06 20:00:00	0.04167
30	2022-12-06 22:00:00	0.4	11.225	-1.105555556	85	10.72777778	47.33333333	11.65	45	135	2022-12-06 21:00:00	0.04167	2022-12-06 21:00:00	0.04167
31	2022-12-06 23:00:00	0.466666667	11.375	-0.883333333	85.61111111	10.90555556	46.72222222	11.85	44	135.25	2022-12-06 22:00:00	0.04167	2022-12-06 22:00:00	0.04167
32	2022-12-07 00:00:00		11.575	-0.827777778	84.66666667	11.05555556	46	12.025	43.5	130.25	2022-12-06 23:00:00	0.04167	2022-12-06 23:00:00	0.04167
33	2022-12-07 01:00:00	0.6	11.75	-1.127777778	82.77777778	11.20555556	45.16666667	12.175	42.75	126.75	2022-12-07 00:00:00	0.04167	2022-12-07 00:00:00	0.04167
34	2022-12-07 02:00:00	0.6	11.875	-1.2	82.44444444	11.33333333	44.77777778	12.35	42	123	2022-12-07 01:00:00	0.04167	2022-12-07 01:00:00	0.04167
35	2022-12-07 03:00:00	0.6	12.025	-1.216666667	81.94444444	11.47777778	44	12.5	41.5	120.5	2022-12-07 02:00:00	0.04167	2022-12-07 02:00:00	0.04167
36	2022-12-07 04:00:00	0.5	12.15	-1.288888889	80.66666667	11.62222222	44	12.625	41	116	2022-12-07 03:00:00	0.04167	2022-12-07 03:00:00	0.04167

Figure 36 Sample of non-value error in the resulting recording

Visualization of the real-time data view is adjustable in the service provider portal (Figure 37). The service provider's user face offers the possibility to sort data by sensors and time period. Data can be downloaded in CSV and XLSX formats for analysis and calculations.

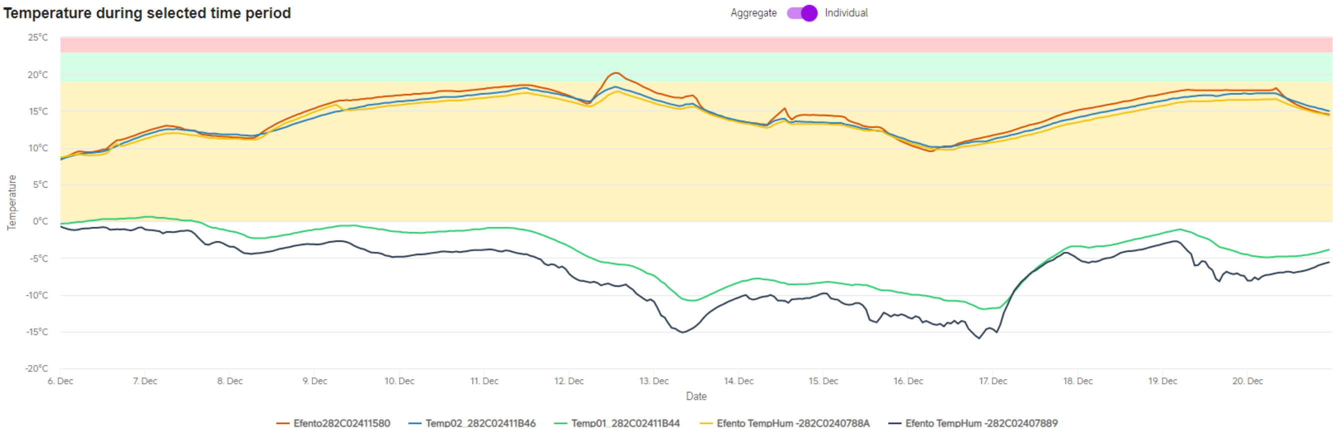

Figure 37 Display from service provider platform

5. Conclusive remarks on collected data

The analyzed data were collected for 4 weeks, sufficient time for the growth of the biological particle. In the chart (Figure 38) of the analyzed data, the lowest temperature is +10°C, which is 5°C lower than the graph of the entire structure. The reason for this choice is the sensor's location, which is directly on the surface of the metal structure.
The obtained data shows that sensors Temp 01, and Temp/HUM 01 (inside the wall) have been below the permitted limit during the entire monitored time. The humidity is also intermittently higher than allowed at these points.

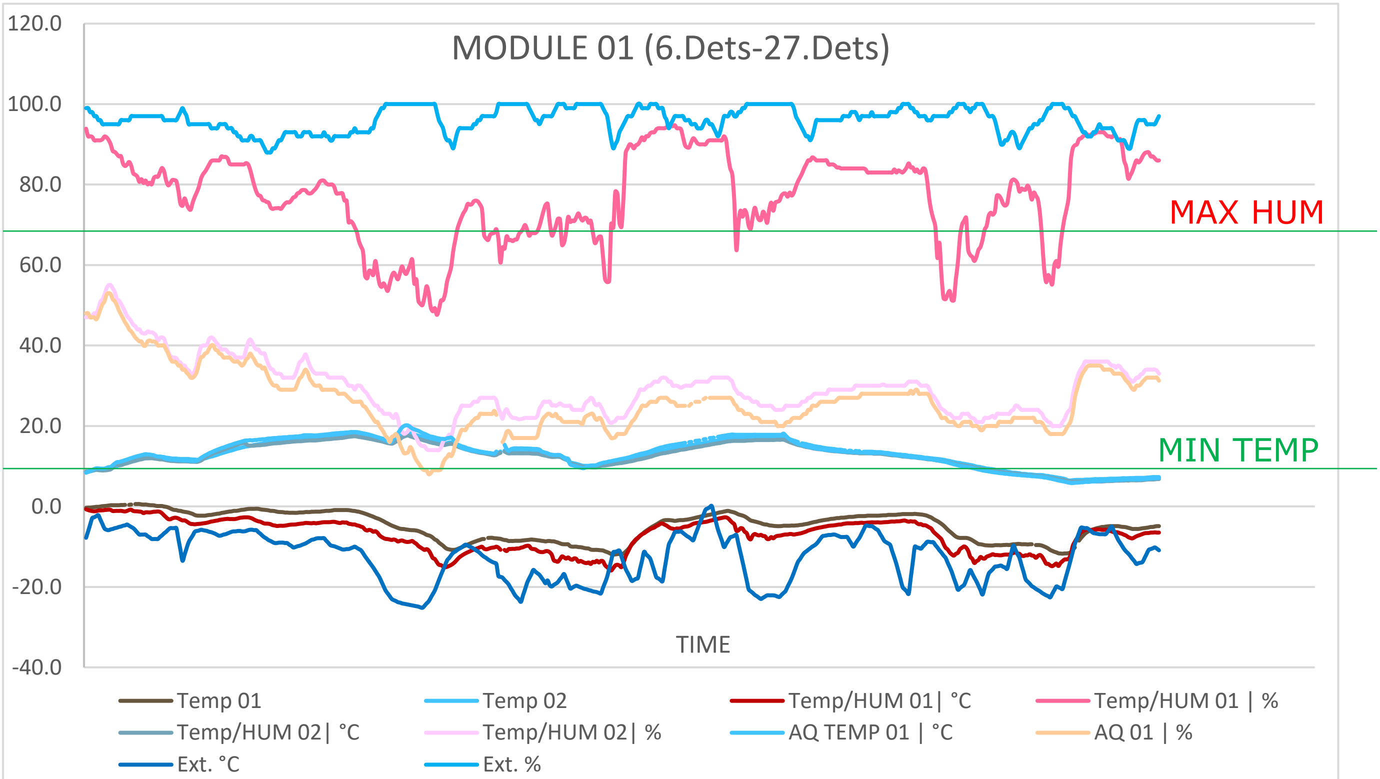

Figure 38 Monitoring data of Module 01, Room 01

The most significant deviation in this analysis requires more detailed studies to determine whether a change needs to be made in the module's construction design, installation process, or environmental or structural health measurement. At present, more measurement results are required to draw broad conclusions. However, based on the given data, we can safely conclude that the monitored result does not meet the given conditions.

Conclusion 1: Module 01 has not been in the required environmental conditions since installation and needs technical analysis after the installation. A technical examination must be done at measuring points Temp 01 and Temp/HUM 01. If damages occur, they must be reported, and maintenance and repair work must be done. The damage size must be considered in the LCA module D when assessing the quality of the material. When detecting deviations and in the expert report, the real reason for the findings must be stated. It must be considered that the found deviation could also be a misinterpretation and must be studied. In the case of misinterpretation, the data collection and reference values, as well as data analysis, must be re-evaluated.

Based on the obtained data, the modules in the outer corners of the building need careful supervision, monitoring, and a maintenance plan. It is necessary to pay special attention to the metal details inside the construction. In the IoT measurement results of the outer corner of the last module (sensors Temp 01 and Temp/HUM 01), the temperature has been lower than the reference value we have set during the observed period. Such deviations show that during the installation process, the foundation of the building is not isolated, even though the building was heated with a temporary heating solution.

Conclusion 2: The data show that the installation process must be stricter regulated. In the installation instructions of the modules, a requirement point must be added that the insulation work of the building foundation must be carried out within two weeks after the start of heating the building. The instructions must specify the temperatures at which this requirement applies—simplifying, for example, from autumn to spring if the outdoor temperature is +5°C and below. If the required conditions are impossible to set, an expert examination must be carried out when the conditions normalize, and it must be assessed whether the construction materials have suffered permanent damage. Temporary covers of insulation during installation can be used.

Conclusion 3: Based on the received data, it was found that at this time, the highest quality rate could not be automatically used for the module’s materials in the LCA D module calculations as there have been deviations during the monitored time.

Future work and possible use cases

Calculations and design based on monitored data are continuous improvement processes. Continuous data collection and perform periodic analyses in the projects for furthermore accurate data and to make higher quality decisions based on it will be continued. Automatic alarm systems will be designed to prevent permanent dangerous situations. Operations processes and manuals will be created to prevent and eliminate damage. The collected Big Data will be used in product LCA calculations and declarations. Using real data in LCA calculations and in automated assessments. Based on the collected Big Data will be designed CO_2 emission reduction process, and the design-improving process will be established.

SUMMARY

In this work, the IoT implementation concept for modular wooden house life cycle assessment in order to achieve a circular economy was proposed. To reach this goal, life cycle assessment as a concept and the calculations it includes were studied as well as the role of IoT for circular economy and data acquisition and monitoring. The concept was tested on a small scale in modules with narrowband IoT sensors monitoring humidity and temperature.

The conclusion of this work is that IoT is a simple and reliable technology for monitoring wooden modules as building products and enables the development of fully circular buildings that can be handled, exchanged, reused, and maintained as functional units (one module). IoT technology enables quick and easy monitoring of critical aspects and produces the necessary reliable and independent data flow for module-by-module evaluation of product design and materials. With the adoption of IoT, several additional applications arise, such as inputs for product design innovations and setting the periodicity of maintenance work. Taking one module as a unit of building products enables the use of IoT data-based design or redesign. With IoT data, we can declare the impact on the environment and also reduce it because preventive actions can extend the life of the product. It is possible to use Six Sigma as a discipline and adopt a module as part of a continuous improvement methodology. It is also possible to use the same technologies and methodologies for the handling of modules to eliminate process deficiencies. IoT data will certainly provide findings for quality management.

IoT capabilities to monitor modules in warehouses and during transport significantly save time and money for monitoring. The LCA concept was created to assess the environmental impact of modules in a way where each project is viewed as one life cycle that is manageable if sufficient data is available. Here we can see that IoT offers the possibility to collect real data for such assembly and, acting on the basis of this data, to ensure suitable conditions for wooden modules for a very long time.

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