FINAL REPORT ON RESEARCH ACTIVITIES

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Abstract

This paper provides a summary of advanced beyond the state of the art created by InnoRenew CoE in the following fields: materials, business support, ICT, and sustainable buildings.

Introduction

InnoRenew CoE and its partners have made significant contributions to the state of the art in the fields the institute was designed to address. Contributions range from applications of existing techniques and methods to new materials and methodological innovation to ground-breaking advances that are reshaping the way we think about coatings for building (and other) materials. Each of the areas targeted by the project, Materials, Business Support, ICT, and Sustainable Buildings, have seen notable advances, in a large part due to the interdisciplinary collaboration within InnoRenew CoE and with its external partners. Combining a wide range of expertise related to sustainable construction inside one institute then leveraging the strengths of its partner network provide an unmatched opportunity to drive innovation and set an international agenda for sustainable building research with bio-based materials.

This report summarises the advances gained within the InnoRenew project, and the advances enabled by the project that were realised by InnoRenew CoE and its partners in new projects.

The fields where considerable advancements of knowledge were delivered are:

Materials. activities concerning the utilization of the components of wood and bio-based materials. This includes bio-based materials ranging from solid wood, fibres of different dimensions, and chemical precursors derived from wood. The highest priority topics were identified as:

- Wood modification (bulk and surface modification)
- Wood composites (development, testing, production methods, upscaling from lab to industry)
- Coatings/surface treatments (development, new material sources, improved/new functionality)

Business support. activities largely oriented towards supporting enhanced RDI utilisation in Slovenia's forest-based sector and beyond. The highest priority topics were identified as:

- Material and component testing as a service
- Innovation Management research and implementation
- Product development services including market research
- Proposal and grant writing to support business in their pursuit and implementation of RDI activities

ICT. activities focused on product and process improvement through data collection and analysis, supporting further RDI activities with data, and providing useful data to the public, policy makers, industry, and researchers. The highest priority topics were identified as:

- Sensors and their collected data (development of new sensors, improved use of existing sensors, storage, management, and analysis of collected data)

- Industrial process optimisation (improved production and material efficiency, smart production, data collection and analysis, connecting and integrating value chains)
- Building information modelling (expanding the BIM format, including data from sensors in use, hosting a BIM library, supporting development and use of BIMS in regional businesses)
- Public data explorer (to share, disseminate generated data, and link it with other open data platforms)

Sustainable buildings. activities concerned with macro construction, structure monitoring, energy efficiency, and the quality of living within buildings. These activities focus on promoting REED principles in the sustainably built environment by targeting the building design process and the marketability of these new buildings. The highest priority topics were identified as:

- Hybrid systems (develop, test, and increase the use of renewable materials in hybrid building systems, such as steel-wood, glass-wood, concrete-wood, etc.)
- Smart buildings and districts (use sensors embedded in buildings to optimise resource use and building management, optimise resources use in districts, reduce maintenance cost and time with active surface modifications for wood elements, etc.)
- Interior quality (use design and material selection practices to create positive health impacts for building users and reduce negative health impacts)

Advances beyond the state of the art

The InnoRenew CoE project was organized to establish a new research institution, support the RDI environment related to wood and built environments in Slovenia and beyond, and its contributions were organised broadly into four categories: Materials (Section 2.1), Business Support (Section 2.2), ICT (Section 2.3), and Sustainable Buildings (Section 2.4). The advances summarised in this section highlight the main contributions driven by the project through InnoRenew CoE's own work, collaboration with project partners and with new partners, as well as close work with industry, government, and the public.

2.1 Materials

2.1.1 Wood modification

Research was conducted to enhance properties, extend service life, and create new functionalities of wood and other bio-based materials through selected modification processes based on deep knowledge of material properties and understanding of its transformation mechanisms. The focus was directed on both bulk and surface modification methods supported by the comprehensive and multiscale characterization of developed materials (Báder et al. 2020, Han et al. 2022). Full understanding of the hierarchical structure of wood (and other biomaterials), combined with computational modelling and screening of material properties with high-resolution non-destructive techniques advanced understanding the material's structure (Ponnuchamy et al. 2020). Subsequently, designing new and targeted functional biomaterials with the specific properties became simpler.

The progress beyond the state-of-the-art in the field of wood modification was achieved by the development of original treatment solutions (Neyses et al. 2021) as well as by combining already available technologies (bulk and surface) into hybrid modifications (Sandak et al. 2021a). The effort was directed toward designing advanced materials with improved functionality, performance, aesthetics, versatility, and sustainability, utilizing a bottom-up approach. A novel methodology for defining wood as a numerical hierarchical structure combined with the mathematical description of processes enabled designing targeted sequences of processes leading to the production of materials of desired properties (Ponnuchamy et al. 2020). Implementation of materiomics led to the rapid development of novel materials without the extensive trial-and-error learning process. In this case, computational models were used as bridges between material description and real-life performance. Consequently, mathematical, statistical, and computational methods were used to create virtual materials as a function of property requirements. Special emphasis was given to the development of new materials through green and environmentally friendly processes (Kutnar et al. 2021) and implementation of biomimicry as a source for inspiration for materials design (Sandak et al 2020a).

One of the most notable advances was the development of engineering living materials (ELMs) capable of interacting and responding to environmental conditions, which are considered the most relevant contemporary revolution in materials science and engineering (Sandak 2023). ELMs are defined as materials composed either entirely, or partly, of living cells. Due to unique functionalities and outstanding properties, they outperform current examples of "smart materials" (Figure 1).

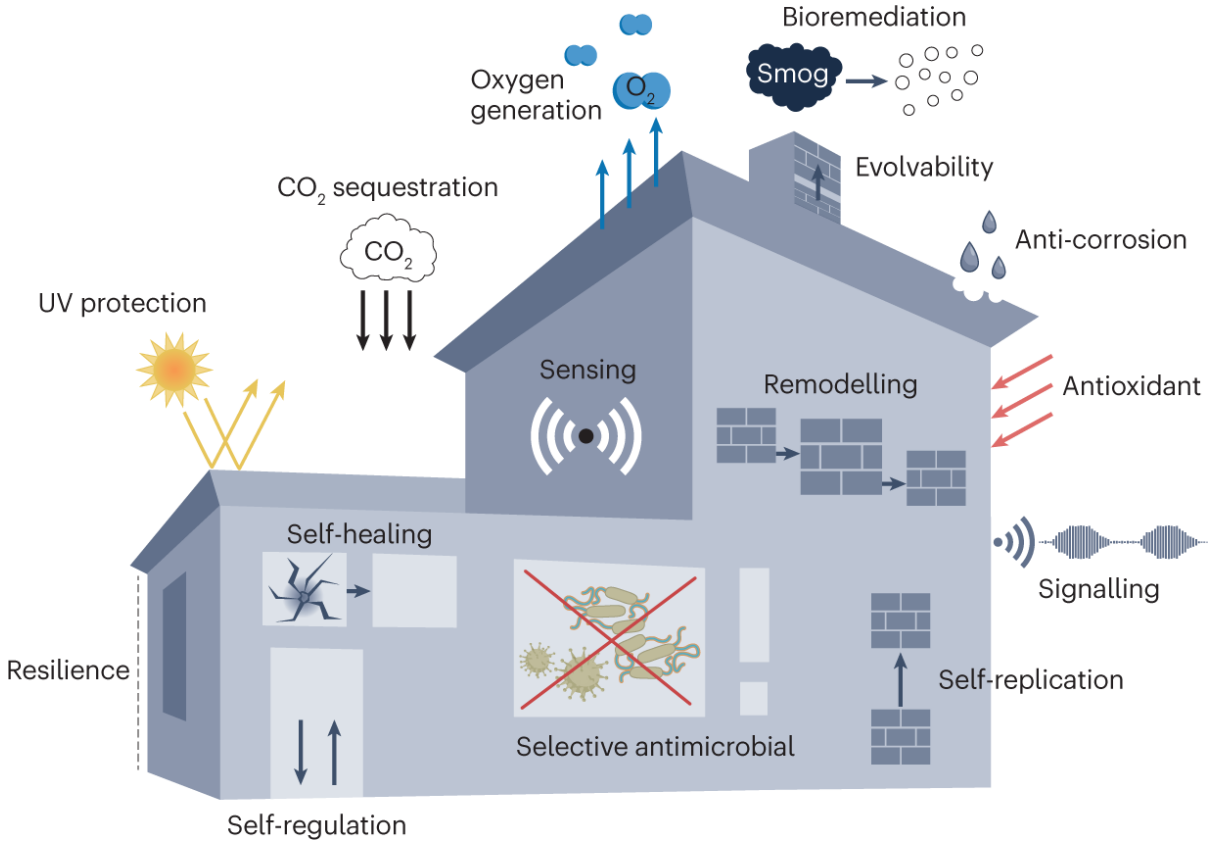


Figure 1 Opportunities for use of ELMs in architecture (Sandak 2023).

Significant progress was made in the advancement of the new process and product quality control procedures (Sandak et al. 2019a). This activity allowed understanding of the physical and chemical characteristics of modified biomaterials. Different multivariate process control tools were adopted for state-of-the-art wood modification processes, allowing real-time and at-line monitoring of processes. Low-cost but reliable sensor solutions were developed for routine quality assurance of modified wood production, installation, and during its use (Sandak et al. 2021b). Finally, procedure/protocols(s) for the raw resources' characterization were proposed as input for the optimization of the modification processes, with a primary focus on thermal, chemical, and surface treatments (Sandak et al. 2022).

Today's bio-based building materials, even if well characterized from the technical point of view, often lack reliable models describing their performance during their service life. Experimental characterization of biomaterials properties at different stages of their transformation is a key issue in future product and process optimization and numeric models' validation (Chuchala et al. 2021). A multi-sensor measurement chain for the acquisition of properties at different scales (macro, mezzo, micro, nano) was established. Innovative products which have not yet demonstrated long-term performance were assessed in terms of operational durability (Sandak et al. 2018). Three approaches were confronted: artificial and natural weathering and inspections of the real buildings in the field (Petrillo et al. 2019). Moreover, the weathering trials were conducted in different climatic conditions (Poohphajai et al. 2023). These allowed for predicting the expected properties and functionality over elongated service lives, minimizing environmental impact and reducing the risk of product failure (Sandak et al. 2021c). It is expected that the extensive database of performance properties and original numerical tools developed for programming the service life, maintenance schedules and end-of-life scenarios, including circular use will increase architects' confidence in using modified wood (Sandak et al. 2019b).

2.1.2 Wood composites

Wood composites and engineered wood products are an integral part of the built environment. InnoRenew CoE was and is active in projects that explore and push these products beyond the state of the art. The Renewable Materials Composites Group (now absorbed within the Materials Group) has contributed to the state of the art as follows.

One integral part of composites are the binders and connections. InnoRenew CoE is heavily involved with research on novel adhesive use in composite materials including flexible polyurethanes, modified bio-based adhesives, and wood/polymer blends.

One research path InnoRenew CoE is pursuing is that of flexible polyurethanes (PUR) for use in CLT constructions (Pečnik et al. 2021a). Rigid PUR is currently used in Europe for CLT production, and this research is intended to explore flexible alternatives that offer damping and less rigid connections, reducing energy transfer through a structure. This research started as an InnoRenew CoE start-up project and has received further external funding to investigate the durability of these bond lines in service conditions.

Another ongoing research line is that of biochar as an additive to composite materials. Biochar (activated carbon) is currently often used for purification of water, soil amendments, etc. but it can also be used for the cleaning indoor air and enhancing bonding in composites. Ongoing research projects are investigating the manufacture of biochar (Zouari et al. 2023a) from agriculture residues for use in adhesive systems, VOC absorbing coatings for indoor environments, and as an additive to concrete to improve adhesion with natural fibre reinforcements (Figure 2). Biochar was also used as an additive to improve

adhesion between wood particles in polylactic acid (PLA) blends to be used in food packaging (Zouari et al. 2023b, Zouari et al. 2022, Esakkumuthu et al. 2022). As this is a bio-based and biodegradable material, it is of great value in a new era of bio-based and biodegradable products.

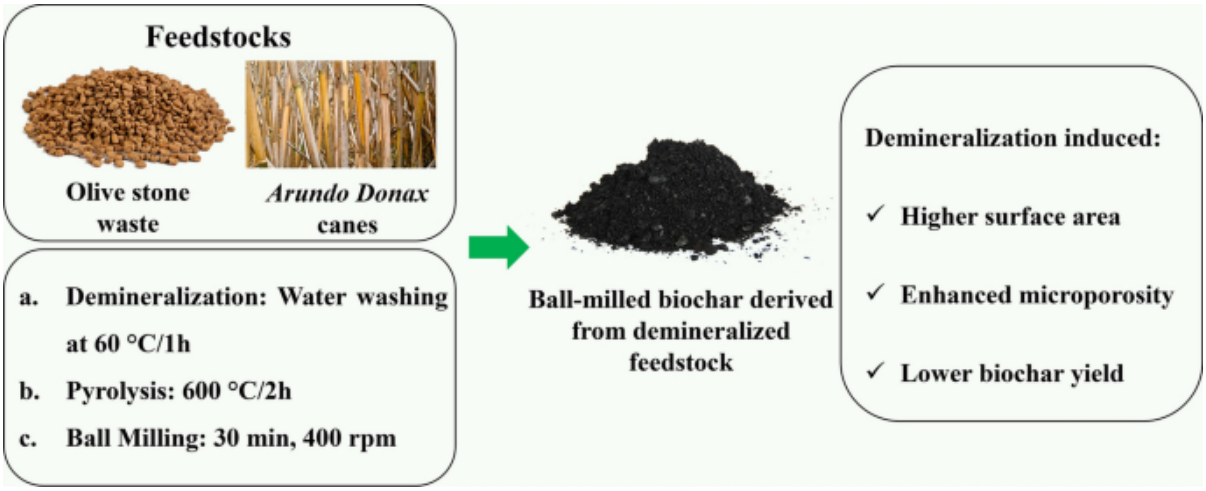


Figure 2 Overview of the process of converting some agricultural residues to functional biochar for using in coatings and other applications (Zouari et al., 2023a).

InnoRenew CoE has explored mechanical properties and measurement techniques in wood composites that previously were not well investigated for relatively new, popular products like CLT. Nevertheless, these properties are of great importance to confidently design and build with. Fracture, fatigue, and creep testing are such measurement techniques that can provide much useful information regarding composite properties but are often not fully utilized in common product analyses.

InnoRenew CoE and collaborating partners investigated fracture properties of wood-adhesive bonds in various environmental conditions to support designers, developers of composites, and to support the development of new composites using different adhesive systems like thick, flexible polyurethane bondlines in CLT (Pečnik et al. 2022b, Sebera et al. 2021).

Fatigue testing was also measured in modified wood products like chemically impregnated beech and pine (Pečnik et al. 2021b). These products are impregnated to improve dimensional stability, modify mechanical performance, and improve resistance to decay. This same method can also make the materials more brittle which can be a dangerous factor when building with them. As new modifications and treatments of wood products are developed, it is also often needed to use more appropriate test, like fatigue in this case. Another such study was used for the development of the now patented MetaDense material (Schwarzkopf 2021, Katner et al. 2019). This material is densified solid wood with a phenolic impregnant. The densification and impregnation create a very durable and stiff

material which is great for certain applications. However, it is unknown how this type of material will perform over time. The time-dependent behaviour of materials and products can also be referred to as creep. Creep is a well-documented phenomena, but it is rarely measured.

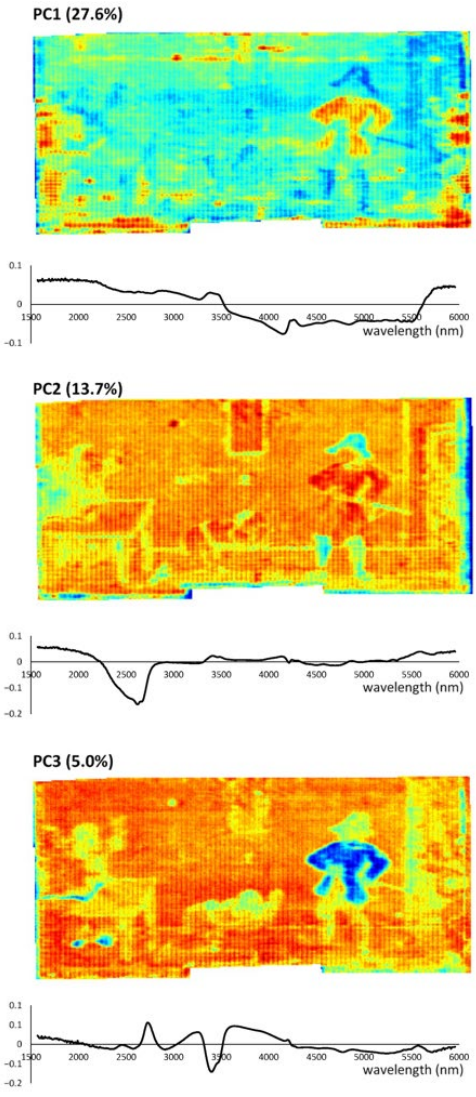
2.1.3 Coatings/surface treatments

Coatings enhance the functional and aesthetical durability of materials by protecting their surface against environmental and biotic degradation. Consequently, paints, coatings and surface treatments not only add to the aesthetics of the material but also protect it against heat, UV, harsh winters, soaking rain, and other adverse weather conditions. Related research at InnoRenew CoE focused on the development of original treatment solutions with minimal environmental impact, using biobased ingredients and green processes (Gordobil et al. 2022).

This work led to the development of several new treatments for wood protection addressing key properties relevant for successful implementation of wood as a building material. An alternative modification protocol based on esterification simultaneously enhancing dimensional stability, hydrophobicity, and photostability was advanced for wood in outdoor applications (Herrera et al. 2020). Biobased fireproofing coatings were designed based on different formulations of phenolic resins obtained from two natural products, lignin and tannins, enriched with inorganic nanoparticles (de Hoyos-Martínez et al. 2021). Affordable and sustainable wooden coatings for façades were developed comprising of biocarbon dispersed in tung oil (Marrot et al. 2023).

One of the research lines concentrated on capturing and exploiting properties that have evolved in nature and employing them for the enhancement of wood/biomaterials properties. The implementation of biomimetics as an inspiration for material improvements and the use of the bottom-up approach for experimental design allowed the development of surface modification and added new functionalities such as self-healing and self-cleaning (Sandak et al. 2023). An innovative and multifunctional coating system that relies on a biologically inspired concept for protecting materials, as an unconventional alternative to traditional coatings, has become a recent area of intense focus (Sandak 2023), even leading to a successful ERC grant and the creation of a new Engineered Living Materials lab at InnoRenew CoE. The concept is based on a technically applicable, controlled, and optimized fungal biofilm formation that effectively protects the substrate surfaces, assuring optimal service life performance (Poohphajai et al. 2021). Its entirely bio-based composition is a great advantage assuring unique sustainability and compatibility with the natural environments. It can be considered, therefore, as an attractive alternative for state-of-the-art wood surface protection solutions.

Another aspect relevant to the development of innovative surface treatment is the material characterization at different scales and with a multi-sensor approach. The development of the characterization laboratory allowed to advance of laboratory routines, develop new methodologies and prototype equipment to assess and monitor coatings performance. The description of intrinsic and extrinsic parameters characterizing selected raw materials at different scales: macro, mezzo, micro, and nano allowed a comprehensive assessment of treatments performance. Advanced imaging techniques were also used to non-invasively characterize, monitor, and evaluate how conservation treatments affect cultural heritage objects (Sandak et al 2021d). Hyperspectral imaging (HI) allowed non-destructive characterization of materials by identifying and characterizing colouring agents, binders, and protective coatings as components of an object's original construction or later historic additions (Figure 3). Furthermore, HI was used to monitor deterioration or changes caused by environmental conditions.



A novel testing protocol for accelerated natural weathering of wood was also developed (Sandak et al. 2021e). The extent of the microstructure degradation and other alterations on the molecular, microscopic, and macroscopic levels recorded in ultra-thin wood samples were confronted with thick references. It resulted in comparable and detailed characterization with simplified sample preparation while still assuring significant shortening of the natural weathering procedure.

Figure 3 Example of hyperspectral imaging used with principal component analysis to non-destructively assess cultural heritage objects (Sandak et al., 2021d).

2.2 Business support

2.2.1 Material and component testing as a service

InnoRenew CoE has built a new research facility. The new building is a unique example of sustainable construction in Slovenia since it was designed and engineered by InnoRenew CoE experts in construction, architecture, engineering, acoustics, mechanical installations,

and living comfort. The facility houses nine state-of-the-art laboratories with research equipment enabling material and component testing for research work and services available on the market. The investment in the research equipment, funded by the Ministry of Education, Science and Sport from the European Regional Development Fund, and partly from European Commission under the ARCHI-SKIN project. The research equipment is used in nine institute's research laboratories:

- The **Human Health Laboratory** is designed to assess human well-being and performance under different indoor environmental conditions,
- the **Composites Laboratory** which houses equipment for the preparation of bio-based composite materials,
- the **Physical Testing Laboratory** for assessing the static, dynamic, and creep behaviour of elastic, plastic, and viscoelastic materials as well as performing in situ testing of the built environment,
- the **Characterization Laboratory** offers morphological, physicochemical, and rheological characterization of bio-based materials,
- the **Microscopy Laboratory** has microscopes and sample preparation devices to analyse a range of materials at micro- and nanoscale,
- the **Acoustic Laboratory** is fully equipped to perform research in architectural and building acoustics, noise control, structural dynamics, and vibrations,
- the **Advanced Manufacturing Laboratory** is a technological hub providing scientific support for a broad range of bio-based businesses as they adapt to Industry 4.0 and beyond,
- the **Engineered Living Materials Laboratory** implements biomimetic principles for the development of new materials and modification processes, and
- the **Workshop and Machine Shop** is a service provider for other laboratories, enabling in-house preparation, conditioning, and storage of experimental samples and prototypes.

2.2.2 Innovation management research and implementation

Slovenia was identified as a region lagging in innovation, and this is particularly noticeable in the country's forest-based value chain. However, Slovenia's Smart Specialisation Strategy identified this industry as having a strong potential for growth. Slovenia implements its Smart Specialization strategy through a new model of development cooperation between key innovation stakeholders, through which it aims to integrate into European and international innovation and development networks, platforms, and consortia. This model is based on nine Strategic Research and Innovation Partnerships (SRIPs).

InnoRenew CoE is a member of two of the nine partnerships closest to its activities and operations:

- SRIP Smart Buildings and Home with Wood Chain (SRIP PSiDL) and

- SRIP Networks for the Transition to a Circular Economy

within which it meets, collaborates and develops solutions and strategies with other members of the partnerships, coming from the fields of business, industry, science, and education. InnoRenew CoE is strongly involved in the work of the SRIP Smart Buildings and Home with Wood Chain (SRIP PSiDL), which is the most aligned with the Institute's mission and activities. Within this partnership, InnoRenew CoE has taken on several formal roles, while at the same time contributing substantively to the partnership's most important development projects. Currently, the largest development project that is being conducted within the framework of the PSiDL SRIP is the design and construction of the largest wooden housing estate in Slovenia, financed by the Housing Fund of the Republic of Slovenia (also a member of the PSiDL SRIP), which is also the largest investor and builder of housing in Slovenia. One of the key and major contributors to the decision of this investor to build with wood were the employees of InnoRenew CoE, through their finesse in the framework of the PSiDL SRIP. This is one of the reasons why InnoRenew CoE was also selected as the expert institution to carry out the consultancy engineering and review of all the project documentation for this construction project. In this context, InnoRenew CoE will also play a key advisory role to the investor and will provide support in the supervision and construction of this landmark investment.

InnoRenew CoE is thus a key contributor to the implementation of the most important development project of the PSiDL SRIP within the framework of smart specialization and, due to the importance of this project and its role in the partnership, will continue to be one of the key stakeholders in defining and implementing the direction of this development in the future.

2.2.3 Product development services, including market research

InnoRenew CoE has been successfully integrating market research into research projects. For example, Slavec et al. (2021) studied how smartphone cameras are used while traveling, especially when visiting outdoor cultural heritage, what are the practices of using smartphone applications when traveling, and what is the role of location-based games in promoting the role of outdoor cultural heritage. The study provides insight into how to combine ubiquitous devices, smart tourism, consumer behaviour, and cultural heritage protection for a more sustainable future. Other examples are a study performed by Sajinčič et al. (2021), who studied the consumers' knowledge and attitudes about lignin-based sunscreens and a study performed by Lipovac and Burnard (2023) that investigated consumer preferences for wood use in desks. With these type of studies InnoRenew CoE has been successfully advancing the research with integrating citizen science principles.

InnoRenew CoE established collaborations with many Slovenian and international companies through joint work on projects and direct contracting. InnoRenew CoE collaborated with over 300 partners from industry via projects or direct collaboration. InnoRenew CoE will make a concerted effort to keep a strong partnership with industrial

partners and continue building successful collaborations. InnoRenew CoE's industrial partners are from the following sectors: the wood industry, construction, agriculture, ICT, architecture, etc.

Since the establishment of InnoRenew CoE, the wood sector in Slovenia has experienced considerable advancement. Some indicators of this progress are:

- From 2017 to 2021 Slovenia increase production of sawnwood for 38%, wood-based panels for 16%, fibreboard for 13%; decreased export of roundwood for 49% and increased the import for 77% (source: FAO, 2023)
- There was an almost 1% increase in RDI in wood manufacturing from 2017 to 2021 for all sources of financing together. For companies only the increase was 3.7% (source: SiStat, 2023).
- The SURS industrial production survey has seen a 27% increase in the sales of wood manufacturing products from 561,284,340 EUR in 2017 to 714,784,222 EUR in 2020 (there is no data for 2021 and 2022 yet), especially in sawn and planed wood (74%), while the sale of paper manufacturing products has slightly decreased, especially corrugated paper and cardboard and packaging from it (-2%), except for paper and cardboard products which increased for almost 5%.

InnoRenew CoE built up collaboration with different stakeholders in developing the New European Bauhaus (NEB) Academy. NEB Academy is the flagship initiative of the European Year of Skills. Following a co-design workshop with international stakeholders University of Primorska established in June 2023 the 1st Pioneer Hub “New European Bauhaus Academy Pioneer Hub for Sustainable Built Environments with Renewable Materials” (NEBAP HUB), which is located at the InnoRenew CoE. Its ambition is to accelerate the transfer and adoption of climate change mitigation knowledge and capabilities to businesses, policy makers, and the public by creating a hub where critical expertise on decarbonising the building stock using renewable materials is gathered, enhanced, and efficiently transferred to society, including policy makers, industry, and other stakeholders. Among the first activities of the NEBAP HUB was to develop a survey on knowledge gaps and needs of the construction ecosystem throughout Europe in 17 languages (results expected Q4 2023).

2.2.4 Proposal and grant writing to support business in their pursuit and implementation of RDI activities

InnoRenew CoE has actively sought additional funding. From their establishment there were 285 proposals submitted. Among them there were 133 international proposals. Over 70 % included industry partners from Slovenia and abroad. There are 6 nationally funded projects and 13 internationally funded projects where InnoRenew CoE collaborates with industry partners.

2.3 ICT

2.3.1 Sensors and their collected data

Sensor networks and IoT systems play a key role in today's scientific and technological development; by their data collection capability novel monitoring and data analytics frameworks can be realized, while integrating AI methods smart solutions can be developed. Throughout the InnoRenew CoE project, researchers achieved numerous results beyond state of the art concerning privacy-aware, secure data collection, data management and data analysis with demonstrating their use for the renewable materials and sustainable built environment RDI activities as well.

A majority of the widely used IoT solutions are based on Wireless Sensor Networks (WSNs) consisting of many sensing nodes. In state-of-the-art solutions, WSNs transfer the collected data to the cloud for storage and further processing. However, this centralized infrastructure has a high security and reliability risk: the connection to the cloud becomes a single point of failure. Furthermore, remote storage also increases the risks of data security and privacy. Using the recent development of embedded technologies, decentralized solutions are a natural answer to the security and reliability risks associated with cloud infrastructures. However, these approaches still suffer from several limitations such as ensuring data security and accessibility.

A potential solution to the challenges posed by decentralised systems can utilise distributed ledger technologies such as blockchains, which makes it important to identify the limitations and requirements for privacy-aware secure blockchain design (Aslam et al. 2021a). Using this knowledge InnoRenew researchers developed a privacy-aware and secure decentralized blockchain based data storage framework with a proof-of-concept implementation, security and privacy analysis, and evaluation for time consumption and scalability (Aslam et al. 2023). The applicability of the solution has been evaluated in the context of energy management for positive energy districts as part of the work realized in the COST action CA19126 – Positive Energy Districts European Network (Aslam et al., 2021).

Nevertheless, decentralized data storage poses other challenges, such as developing secure data analytics methods: distributed data mining is a non-trivial task by itself, but complexity issues also need to be considered. A privacy-aware distributed data mining approach for WSNs (Hrovatin et al. 2022a) was developed that uses a permissioned blockchain to avoid a single point of failure in the system.

To support development in this area InnoRenew researchers provided a blockchain solution as beyond state-of-the-art that relies on semantic Web services to operate in a single data-driven framework (Hrovatin et al. 2022b). This new approach is based on a semantically-driven secure task execution on WSNs that relies on blockchain smart contracts and onion routed task execution driven by semantic descriptions. Our solution respectively provides

role-based access control (RBAC) for query and supports local privacy-preserving task execution (Figure 4; Hrovatin, et al., 2023).

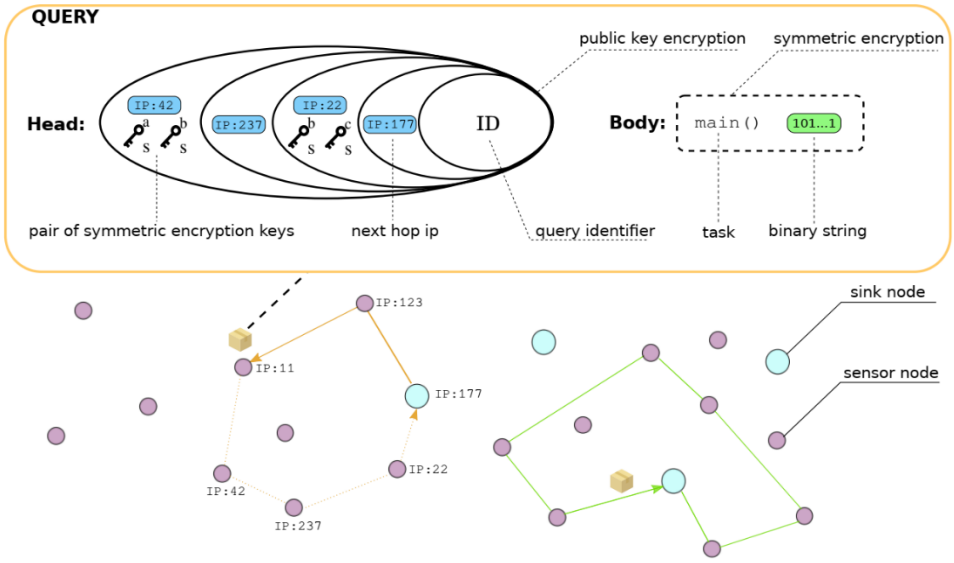


Figure 4 Representation of the query, made of the head and the body. Notice that symmetric encryption keys are not enclosed in each layer of the query head. The figure displays the query's path forming a circuit. (Hrovatin et al., 2023)

Since our novel framework (Mrissa et al. 2022) stores and processes the data as a distributed system the WSNs are organized on two levels: in addition to the sensor nodes measuring the environment we distinguish gateway nodes (or sink nodes) collecting the information from the sensors and storing the data as a distributed system. Gateway placement can be settled in our framework in a dynamic multi-objective manner utilising the lifetime of the network, expected battery usage, or robustness of the installed system. Our researchers developed a simulation environment (Hajdu et al. 2021a) providing suggestions for gateway placements with different objectives. In a recent study (Elhüseyni et al. 2023) a mathematical programming-based optimization solution for gateway placement is presented.

Privacy aware indoor location has received recent attention from researchers and practitioners, especially for practical applications, and several of the challenges discussed earlier are at the heart of this research area. Moreover, the design of WSN remains under investigation and examines many different characteristics as well. We have developed an innovative WSN framework (Tošič et al. 2022a) that introduces a new protocol for querying and performing computations in WSNs while preserving sensor network anonymity and obfuscating computation with the use of onion routing. We also consider the single point of failure of sink nodes in WSNs and substitute them with a blockchain-based application

through smart contracts. This approach is extended by a method to compute with a Convolutional Neural Network on grid-shaped sensor networks (Hrovatin et al. 2022c).

A unified approach to many challenges in decentralized use and management of WSN is Edge Computing. It recently emerged as a new paradigm to migrate data processing close to data sources. InnoRenew researchers considered challenges beyond state of the art in this field as well. Resource usage optimization is a challenge due to the limited capacity of edge devices and is typically handled in a centralized way, introducing performance, security, and efficiency concerns. We developed a decentralized approach that relies on a combination of blockchain and a consensus algorithm to monitor network resources and migrate demanding applications at runtime if necessary. (Tošič et al. 2019a). In another solution we introduced a decentralized architecture tailored for large-scale deployments of peer-to-peer IoT sensor networks and capable of run-time application migration (Tošič et al. 2023a). Routing protocols focusing on latency plays an important role in networked systems; however little attention focused in the last two decades on the trade-off in terms of security and anonymity. We developed a solution for decentralized routing networks to improve fault-tolerance, and latency (Tošič et al. 2022b; Figure 5). Such networks can be used as a communication layer for Edge devices computing huge amounts of data.

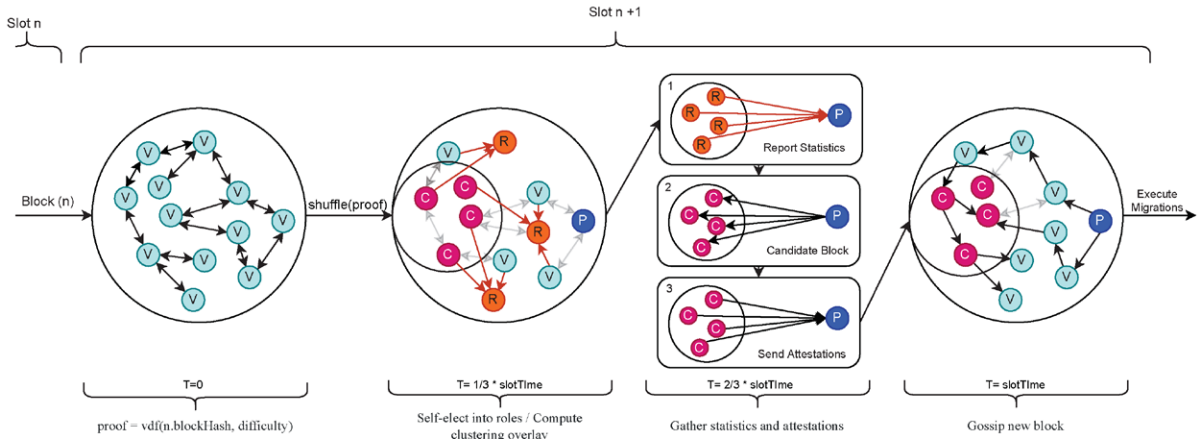


Figure 5 Diagram of the time-synchronous protocol used for application migration using a blockchain (Tošić et al., 2023a)

Finally, for the development of new innovative technologies in WSNs, appropriate simulation frameworks are necessary. State of the art network simulation software such as nsnam NS3 do not consider the specific requirements of WSNs. Our simulation solution PPWSim simulator (Hrovatin 2022d) is developed to study privacy-preserving communication protocols for edge data processing in WSNs.

2.3.2 Industrial process optimisation

The RDI activities in industrial process optimization beyond state-of-the-art covered wood supply chain optimization, optimization of wood processing scheduling, transportation

optimization, optimization of workforce scheduling and optimization of sustainable building design.

Wood supply chain optimization has been active over the past years, but there were only minimal results on the optimization of processes in the waste wood supply chain. We focused on locating the accumulation centres in the supply network in such a way to minimize the costs of transporting waste wood from accumulation centres to processing facilities (Egri et al. 2020). Besides transportation, we also studied economies of scale (Egri et al. 2021) as well as the robustness of the network in case of "the breakdown of facilities" (non-operating accumulation centres). In cooperation with our research partners, we have produced efficient mathematical optimization models with solution methods.

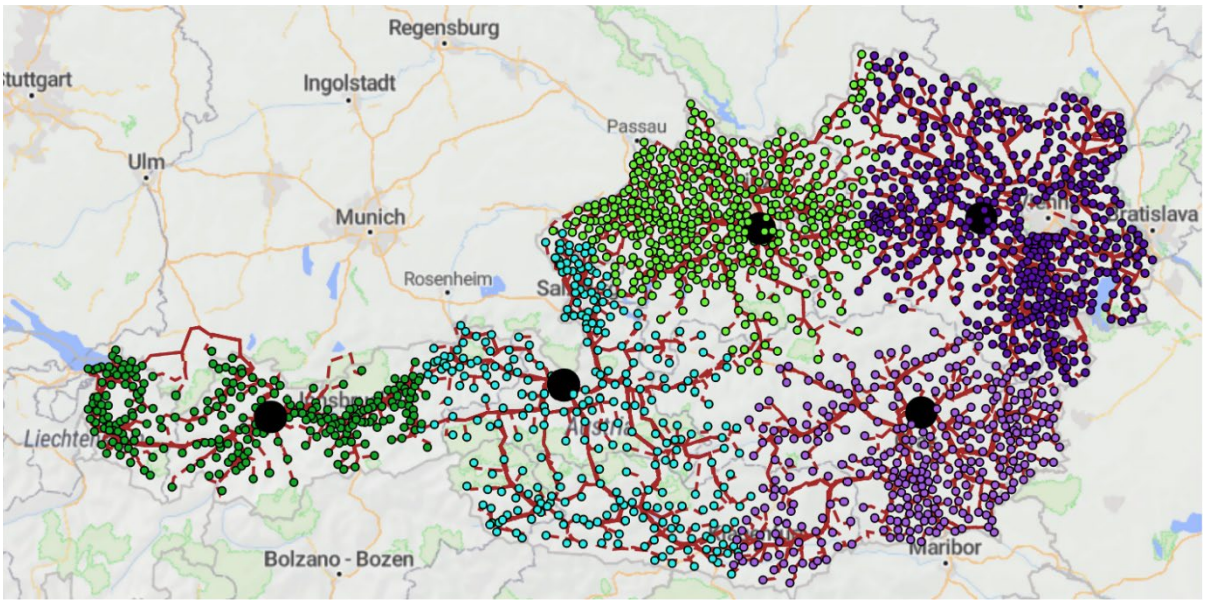


Figure 4 Output of a robust waste wood collection network in Austria (Egri et al., 2021).

InnoRenew was also responsible for the development of a macro-level optimization model in Slovenia that allows for the multi-objective optimization of wood volumes for processing across the entire forestry, wood and paper sector for long-term policy coordinated with the broadest range of stakeholders (Shau et al. 2023). This innovative approach can elevate industrial optimization models for use in macro-level policy making. The model is based on development needs, the businesses and investment plans of different stakeholders, and a holistic assessment of different scenarios for the development of logging, processing, and utilization of wood in Slovenia.

Other important challenges in the wood value chain are related to scheduling problems. In this case, the focus is not on the network level optimisation, but the process optimisation on the nodes. One important step is the processing of the collected waste, which is usually done through shredding, as most end-uses (e.g., energy or chipboard) require wood to be

shredded to a certain size. This research considered the scheduling of a waste wood processing plant, where the incoming wood deliveries are processed by a series of transformation steps to produce shredded wood (Dávid et al 2021a). Different mathematical models are designed for the problem (Ősz et al 2023) to handle the overlapping automated processing steps (Dávid et al. 2021b) to provide as continuous operation as possible. When overlapping is not allowed, then another model is introduced which accounts for the robustness of the problem by considering the uncertainty that arises because of the varying delivery sources and quality (Dávid et al 2021a). Efficient scheduling is also crucial for plywood production processes. The aim of the proposed approach (Ősz et al. 2022) is to minimize penalties for order cancellations and deadline modifications.

Maximizing the value of harvested trees is an important objective of the forest industry. Bucking – cutting logged trees to length for further processing – plays a significant role in determining the ultimate value of a tree. Maximizing bucking value on the forest stand level, finding optimal bucking options for multiple tree stems simultaneously was considered in our research (Dávid 2023).

In sustainable environments in port area the gate operation management can have a significant environmental impact on the neighbouring built environment. InnoRenew researchers developed an efficient model and method for optimizing truck scheduling within a port, using a mathematical model that facilitates concurrent tasks under specific constraints and capacity limitations (Baldouski et al. 2023).

The efficiency of industrial processes is highly influenced by the human resource scheduling. InnoRenew researchers achieved relevant results in this topic as well. A novel, innovative method for long-term shift scheduling was worked out and tested in real environments (Hajdu et al. 2020). Another new approach is using constraint programming techniques to develop efficient personal scheduling. (Cymer et al. 2019). Furthermore, a unified framework for workforce scheduling was worked out and demonstrated its use with the data set of a partner research institute (Tóth et al. 2018)

In optimization applications at InnoRenew building design optimization is also in focus. In standard approaches of architectural design, the different environmental and comfort aspects (such as energy efficiency) are not always optimized. In a cooperation with an InnoRenew project partner we have developed a practical and efficient optimization method for heterogeneous structural frame design (David 2019). As a recent work InnoRenew researchers joined a team of the developers of Energy Design Synthesis as an innovative architectural design methodology. This resulted in a novel algorithm for efficient building shape generation (Figure 6; Storcz et al. 2023).

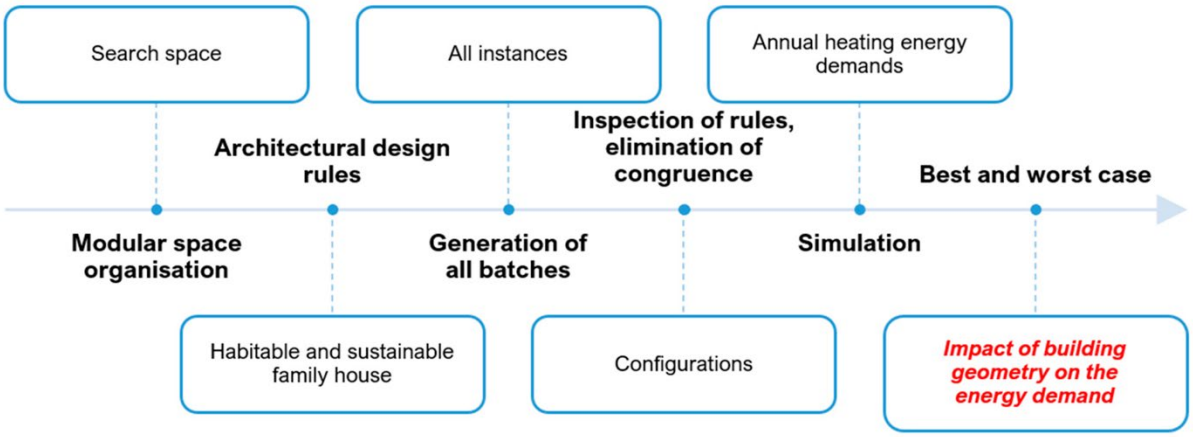


Figure 5 Process configuration for building shape generation and energy simulation (Storcz et al., 2023).

2.3.3 Building information modelling

Environmental quality monitoring plays a crucial role in improving indoor living conditions. Therefore it is crucial information for stakeholders. Consequently, environmental monitoring is relevant to building management from the design to the end-of-life along the whole life cycle. However, building management modelling tools are still limited to static models and lack the integration capabilities needed to effectively exploit environmental quality monitoring data. To overcome these limitations, InnoRenew researchers, together with project partners, designed and implemented a generic software architecture that relies on the attributes of the accessible Building Information Model (BIM) to add a dynamic layer that integrates environmental quality data from installed sensors. (Mrissa et al. 2020). Using the BIM software Revit as an example demonstration tool we have shown that it is possible to display live information on the quality of the environment (temperature, relative humidity, CO2, particles, light) so that end-users can monitor the state of their living environment and take appropriate action to improve its quality.

As a further step beyond state-of-the-art InnoRenew and project partners investigated whether we could contribute to ensuring the well-being of people in buildings by using BIM (Jutraž et al. 2022). We have developed a new methodology for pursuing this research line (Figure 7). We monitored different environmental parameters in the building with sensors: temperature, relative humidity, light and various particle sizes (PM) in a more than 100-years-old house protected as a cultural heritage site of local significance. In addition, we also developed a methodological model for measuring radon and mould. The research followed the whole renovation process between 2017 and 2021 with the use of BIM in three phases. As concluded, the quality of the renovation of a heritage building would be significantly improved if, in addition to the designers/planners (architects, structural

engineers, building technicians, building services engineers, etc.), the renovation process also involved the investors and the future users, who are public health professionals.

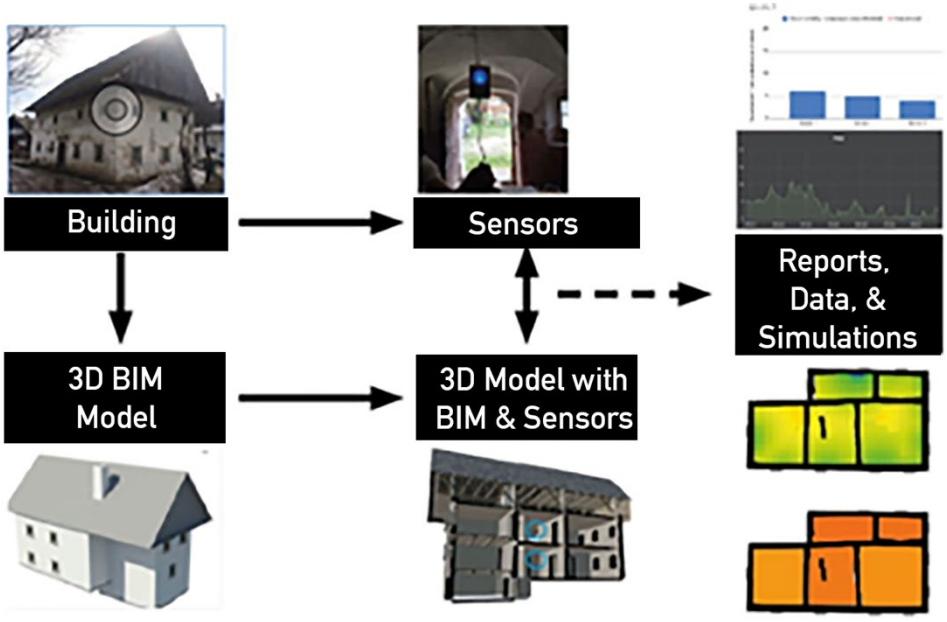


Figure 7 Connection between the cultural heritage building, its digital twins, and the use of sensors, for preparation of analysis and simulations of various environmental parameters (Jutraž et al., 2022 - Translated).

In addition to the direct use of BIM, InnoRenew researchers considered an important - related practical problem of building optimisation. In cooperation with partners from Hungary who developed the Energy Design Synthesis (EDS) methodology, InnoRenew researchers contributed the algorithmic generation of building shape configurations (Storcz et al. 2023). EDS is a methodology for energy aware optimal design of buildings. In this cooperation the integration of the methodology into BIM is studied for which the generation of shape configurations is a well adaptable step. The optimization of structural design on the architectural level and integrating it into the work of architects is a research line beyond state of the art; for this challenge a new methodology and a prototype system has been developed by InnoRenew with project partners. In the software, the efficiency of the optimisation module is crucial to its use, and InnoRenew was responsible for this development in this project (David 2019). The optimisation module and the prototype system itself ensure modularity interoperability and thus potentially can be integrated with BIM systems.

2.3.4 Public data explorer

InnoRenew CoE's main activities related to Public data exploration can be divided into two main topics: development of unified data collection, data sharing and data analytics

framework for sustainable buildings in cooperation with partners, and development of new methodologies for knowledge discovery in data platforms.

InnoRenew CoE, together with University of Primorska, Oregon State University, and the University of Helsinki established a research alliance for sharing information on mass timber buildings performance. In the frame of this cooperation, we are monitoring data from three mass-timber projects in three different climate zones. One of the goals of the alliance is to develop a unified framework for data collection, sharing and analytics through implementing pilots using these mass timber projects (Riggio et al. 2023). Such a unified framework is currently not available. The main difficulties of data integration are due to differences in data collection methods, equipment, and techniques, as well as variations in the number and types of monitored locations and measurement periods. A data integration framework based on “avatars” (decentralized computing agents) has been suggested by InnoRenew researchers (Riggio et al. 2022) and it was compared to state-of-the-art Structural Health Monitoring (SHM) solutions.

Concerning the new methodologies for knowledge discovery, InnoRenew researchers developed novel network analytics methods. An innovative algorithm for networked data collection (Tošič et al 2023b) also allows to store the connectivity structure of the data neighbourhood. Visualization plays a central role in data analytics, but their integrated use in knowledge discovery requires to develop appropriate methodologies. For decentralized network data using Grafana plugins an innovative visualization methodology (Baldouski et al. 2022) was developed by which critical bugs and faults can be identified in a decentralized system.

One of the most fundamental tasks in a data platform is intelligent search. A crucial method in this process is ranking. A graph-based prediction model developed for this goal (London et al. 2018) has several potential scenarios to apply in this direction. Another promising research line is based on the local structure of the networks, called community structure. InnoRenew researchers proved their efficient use in ranking of graph structured data based on communities (Hajdu et al. 2018, Hajdu et al. 2021b).

One of the most compelling use cases for knowledge discovery in graph structured research data is the publication database. Publications form networks in several natural ways such as co-authorship networks or citation networks to name just the best known. Using Benford’s law, publication databases can be analysed (Tošič et al 2021a) which allows to characterize a database, and ranking methods to be customized according to the similarity to Benford’s distribution. Another approach for characterizing publication database is using Machine Learning methods as predictive models (Hajdu et al. 2022) for the future performance of publications (as expected citations, etc). With this characterization, ranking methods can be also customized.

2.4 Sustainable buildings

2.4.1. Hybrid systems

Hybrid building systems combine the advantages of different materials and construction methods to create high-performance buildings and achieve sustainability goals in the construction sector. Wood, one of the oldest building materials used by mankind, is now considered one of the most innovative. In fact, wood is one of the most suitable materials, as it can perform different functions (structural element, flooring, decoration...), offers a wide range of connection options, including gluing and fastening, and - as a raw material - is also capable of capturing carbon from the atmosphere. Studies on adhesives are of great importance for building with wood in seismically active regions. For this purpose, the use of flexible polyurethane adhesives for wood-adhesive composite structures has been studied (Pečnik et al. 2021). It has been shown that the shear strength, elastic stiffness, and strength degradation capacity of the flexible adhesive connections were significantly higher compared to mechanical fasteners commonly used in seismic-resistant timber connections.

Wood and materials made from it offer a wide range of appearances, from traditional rustic materials to modern design products. Facades, the outer skin of structures, play a critical role in a building's performance and aesthetics. They influence both the exterior environment and the interior performance and comfort of a building. Recent trends in the use of timber products as façade elements have been presented in a review (Sandak et al. 2020b). Several innovative solutions were presented in the form of successful buildings, showing the best architecture from around the world and inspiring a new generation of architects. The design freedom offered by wood was highlighted, emphasizing non-standard architectural solutions that establish a close connection with nature and improve human well-being. At the same time, new developments in the field of wood modification offer innovative products with improved properties of natural timber. The use of novel wood applications on a building’s façade are demonstrated as part of the InnoRenew CoE building itself.

Research conducted at IR also includes advanced bio-based materials. With the increasing emphasis on sustainable buildings and greater environmental awareness, bio-architecture has emerged as an alternative to conventional building techniques. This approach is consistent with EU developmental and societal goals that encourage the use of biobased products in modern buildings. Despite the potential of bio-based materials, there is a knowledge gap among architects and civil engineers regarding their optimal use, especially for building facades, which is the subject of the book Bio-Based Building Skin (Sandak et al. 2019b). The book addresses a broad audience of architects, engineers, designers, and contractors by providing a compendium of material properties and showing several successful examples of the use of bio-based materials as building skins. The book also introduces the latest trends in material selection and installation systems, while presenting

the innovative functions of facades with an appropriate level of detail. Selected case studies of buildings in various locations are used to demonstrate the successful implementation of various biomaterial solutions that define unique architectural styles and building functions. The book was published open access and was downloaded 76000 times, which proves that it appeals to a broad audience including researchers, architects, engineers, designers and building contractors.

Another way to increase building sustainability is to consider the use of renewable materials for retrofit opportunities. A comparative analysis of the current framework in Bosnia and Herzegovina and Slovenia was conducted (Gajić et al. 2021). Indeed, sustainable approaches to retrofitting are necessary due to the required energy efficiency. As such, retrofitting the building stock is an effective way to reduce global energy consumption and decrease the exploitation of resources. Unfortunately, the implementation of sustainable materials for energy retrofits is held back by gaps in legislation and effective strategic programs, the availability of bio-based materials, lack of knowledge about the use and maintenance of renewable products, and marketing lobbies. The role of green solutions and low-carbon economy growth is particularly important in developing countries that cannot afford innovative energy recovery systems but have significant, amount of poorly managed building stock. Residential retrofits in Bosnia and Herzegovina and Slovenia were analysed to address indirect causes, examine the legal background, and review strategic frameworks that identify potential barriers to implementing recommended retrofit solutions based on renewable materials.

2.4.2 Smart buildings and districts

The interdisciplinary research of smart building and districts at InnoRenew CoE focused on intelligent monitoring of buildings (including alerting systems) and developing privacy aware technological solutions for energy transition concepts such as positive energy districts.

Building monitoring is driven by the equipped smart solutions typically based on Wireless Sensor Networks (WSN). Typical approaches to smart buildings rely on cloud facilities for data storage and processing and autonomic computing to manage buildings along their life cycle (conception, construction, use, and end of life). However, these approaches have several drawbacks: dependency on cloud providers, heavy network usage, high network latency, privacy, and security concerns. Our approach beyond state of the art is based on edge computing to take advantage of the new generation of WSN devices and reduce the environmental cost of building monitoring solutions. We are focusing on air quality monitoring (Mrissa et al. 2022) as a major asset to improving quality of life and building management. We have demonstrated the applicability of our work with a set of pilot buildings of diverse types (public and private), geographical areas (e.g., north, west, central, and eastern Europe), living conditions and usages (residential and non-residential). For the autonomic edge computing technology, we have developed a distributed data mining solution for analysing indoor air quality (Hrovatin et al., 2022a). In our blockchain based

approach contracts are used to construct an onion-like structure encompassing the Hoeffding trees and a route (Figure 8). To validate our approach, we analysed the accuracy of Hoeffding trees in predicting CO_2. In another study, using blockchain based edge computing we presented a decentralized solution for monitoring network resources by validating the approach by a cultural heritage use case to measure and process temperature and humidity data (Tošič et al. 2019a).

Structural health monitoring (SHM) is a key factor in supporting service life management. As a recent change in construction industry, mass timber construction systems integrating engineered wood products are becoming realistic alternatives to traditional multi-story buildings. Concerning the limitation in experiences with these buildings it is crucial to develop smart SHM systems to monitor the performances of these buildings. However, there is a huge limitation in the use of state-of-the-art SHM approaches such as the shortage of unified strategy of data collection, processing and analysis and the limited usability of predictive tools. Our conceptual approach suggests the use of "avatars" as software agents being a Web based layer on the top of the sensing devices (Riggio et al. 2022). The suggested solution supports robustness, high level and large-scale interoperability and data processing. The new approach overcomes many of the limitations of traditional centralised SHM systems and goes beyond the current state of the art. To set up a testing environment for our suggested unified framework three mass timber buildings in three different climate zones started to be monitored (Riggio et al. 2023).

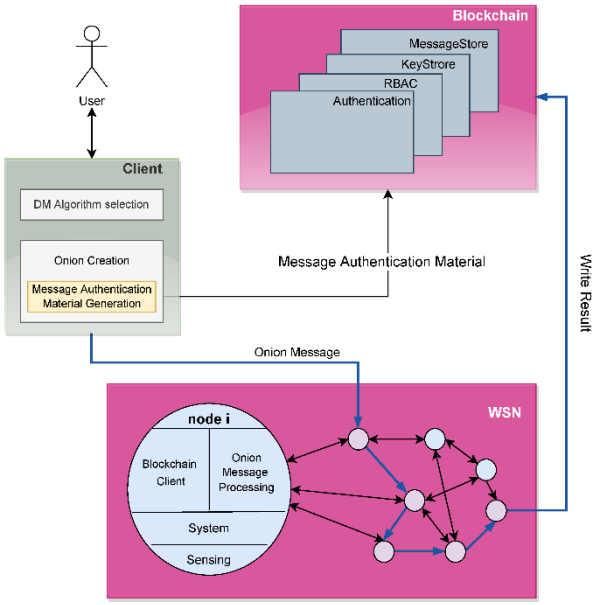


Figure 8 Architecture of a secure, distributed data-mining system for WSNs (Hrovatin et al., 2022a)

Indoor location systems have been developed progressively in the last two decades by the technological advancements of smart devices. It has numerous applications for sustainable buildings such as structural engineering on the technological side and behavioural studies or health monitoring on the human side. Current solutions, however, mainly rely on wearable devices, cameras, or sound signal analysis, which are intrusive and might violate privacy. InnoRenew researchers developed an innovative privacy preserving non-intrusive implementation of indoor location based on WSNs. (Tošič et al. 2019b, Tošič et al. 2022a). The proposed solution could be applied for structural health monitoring, studying behavioural patterns of a building's occupants and health-related issues such as locating

lost patients with memory and orientation disorders, fall detection, and identifying violations of social distancing, counting the number of persons in a room, and determining when and which room needs surface disinfection due to over-utilization, etc. As a case study for this novel approach a fall-detection system was developed (Tošič et al. 2021b) in which a Convolutional Neural Network based Machine Learning solution was integrated for detecting falls (Hrovatin et al. 2022c).

In smart districts one of the key challenges is the development of efficient energy management with minimum environmental impact. Energy transition is usually defined as the change in the composition (structure) of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system. At the urban level, one promising approach to reach the above goal is the concept of positive energy districts (PED), a growing trend in the EU that requires actors to perform write and read operations on a neighbourhood scale where governance competences are typically absent. We have developed a decentralized privacy-aware data management framework that enables actors to store, read, and modify data in PEDs (Figure 9; Aslam et al. 2021b).

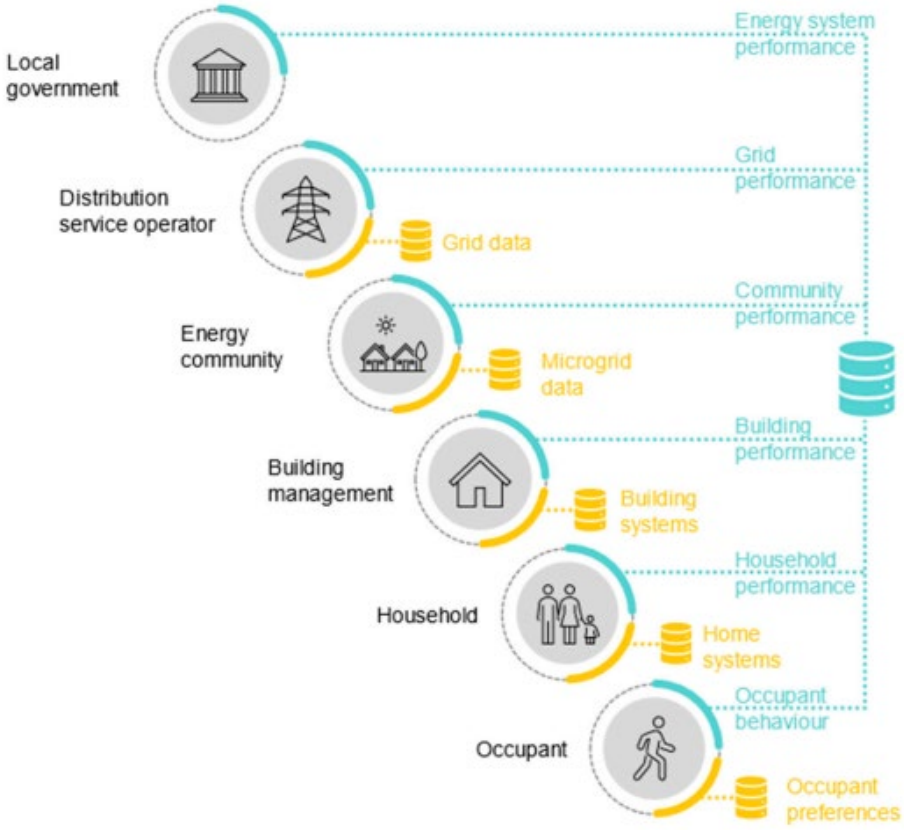


Figure 9 Multilevel data generation in the positive energy district scenario. Gold indicates scale-specific, while blue indicates multiscale data (Aslam et al., 2021b).

The prototype system demonstrates how privacy-aware digitalization can support the development of decentralized energy governance with integrating access control, encryption, blockchain, distributed hash table, and ring signature. In this research a role-based model to manage interactions with data on PEDs is also presented (Aslam et al. 2021c). This includes the identification of actors expected in PED development, a specification of permission requirements based on their roles in PED.

2.4.3 Interior quality

One of the main interdisciplinary focuses of ICT research at InnoRenew is the development of technologies to support monitoring and analysing interior quality. Research on this direction focuses on air quality monitoring, blockchain technology in indoor health monitoring, Building Information Modelling (BIM) and healthy built environment, and behavioural studies in healthy built environment.

As we spend most of our time indoors, indoor air quality (IAQ) monitoring is essential to ensure healthy living. It also contributes greatly to improving building performance and reducing energy consumption. Current IAQ monitoring systems are generally based on WSNs and organized in a centralized manner with cloud data management infrastructure. These solutions have serious limitations in data privacy and security. Decentralised approaches such as edge computing offer a good alternative, but distributed computing still faces privacy issues - to name just one: the data collected requires basic security protection as it describes physical phenomena that can reveal activities in the monitored space. For example, changes in CO_2 and temperature can indicate human presence in a room. The privacy aware and secure decentralized IAQ monitoring system developed by InnoRenew researchers with project partners (Mrissa et al. 2022) provides an advance beyond the state-of-the-art that makes use of the data while providing security and privacy for those in the monitored building.

Given the sensitivity of data collected about buildings and the users within them, recent technologies such as blockchain can offer a secure technological framework for processing interior quality data. InnoRenew researchers studied the state-of-the-art approaches in health monitoring and developed novel conceptual blockchain based solutions to advance the field (Tošič et al. 2018).

Another potential technology to integrate with interior quality measurements is the Building Information Modelling (BIM) as presented in Section 2.3.3.

Behavioural studies in the built environment can be also supported by ICT research both methodologically and by technological point of view beyond state of the art. Our researchers together with partners from Prague analysed the changes of physical activity patterns of elderly population in the Czech Republic during the pandemic period (Janovsky et al. 2022). This information for older adults is crucial to their doctors, and social workers to assess the impact of pandemic measures on the level of physical activity of their clients.

Physical activity was statistically compared according to the physical, demographic, and social conditions of the participants.

Another research on behavioural studies at InnoRenew is using social network analysis and influence maximization algorithmic methods for improving the human stress in built environment (Lipovac et al. 2019, Lipovac et al. 2020). Chronic stress in humans can substantially impair functioning of organizations. Our novel methodology concerns the social network through which stress can spread. Psychosocial interventions targeted at the most contagious people can efficiently improve organizational functioning. The use of our novel methodology was demonstrated on the use case of employees working in healthcare institutions. The methodology was developed further for interventions in a dynamic manner (Hajdu et al. 2021c).

Through other studies, we have additionally studied the complex interplay between indoor environments and human well-being, focusing on the important role that material selection and ergonomic settings play in fostering human wellbeing.

One of the crucial outcomes that emerged from our research pertains to the integration of wood as a promising material for lowering stress in people. One of the studies, which examined stress responses in office settings, has yielded important insights about designing spaces for wellbeing. By comparing offices treated with oak and walnut wood with control settings (Figure 10), we have shown that wood's presence can lower people's stress levels, thereby presenting architects and designers with an option to design environments that can support the wellbeing of building occupants. This was one of the first robust studies that showed wood can be a promising addition to indoor spaces to improve people's wellbeing (Burnard and Kutnar, 2020).

Figure 10 Office environments compared to determine how stress and stress recovery may be affected by materials used in furniture. i - plain white; ii - white oak; iii - black walnut (Burnard & Kutnar, 2022).

Using aesthetics in fostering positive indoor experiences has been another cornerstone of our research. With several studies, we have shown that different wood materials experienced through different human senses tend to be preferred among people of different ages, and in different contexts and countries. With this we have contributed knowledge that goes beyond the state-of-the-art, showing that simply adding wood to interior spaces can improve people's aesthetical experience in numerous situations.

In one study, we examined people's preferences for wooden desk materials and designs, and discovered common patterns in preference that can guide designers in creating visually appealing indoor environments. By discussing the intricate interplay between wood materials and desk designs, we have provided another way to improve quality of interior spaces (Lipovac and Burnard, 2023).

In another study focusing on aesthetics and comfort, we investigated perceptions of different types of materials used in handrails among older building users from two countries – Slovenia and Norway. We have shown that different wooden materials were generally preferred over steel, whether participants examined the materials only tactilely or tactilely and visually, and regardless of participants' country of residence. We have also identified specific properties of materials that are associated with higher material preference, such as perceived naturalness and warmth. With this study, we have therefore shown that using wooden handrails in interior spaces may improve the comfort of building occupants (Lipovac et al., 2022).

The tactile dimension of human-material interaction has also been examined in other studies. Our evaluation of thermal properties and user perceptions of tabletop materials has shown that wood-based materials tend to be perceived as more tactilely comfortable and suitable for various activities (Figure 11; Podrekar et al., 2022a; Lipovac et al., 2020).

We have also focused on furniture in a broader sense, and examined whether school furniture is suitable to the body dimensions of students. A significant mismatch between students' body dimensions and furniture was found across different ages and genders. We have shown that to ensure ergonomic and conducive learning environments and improve student comfort in classrooms, schools should introduce adjustable furniture that is beyond state-of the-art (Podrekar et al., 2022b).

In a related study, we aimed to understand teachers' perspectives on reducing sedentary behaviour among students in the classroom without hindering the teaching process. The research found that most teachers acknowledged a mismatch between student body sizes and furniture. While concerns about disruption were reasons for being against using standing desks, teachers generally found it feasible to incorporate physical activity breaks during classes. The findings thus suggest that physical activity breaks might be a feasible approach of improving wellbeing of students (Podrekar et al., 2020a).

Figure 11 Example desks used to learn preferences and performance of different desk materials (Lipovac et al., 2020; Podrekar et al., 2022a).

To further promote well-being of school-aged children and adolescents, we translated the world's first International school-related sedentary behaviour recommendations for children and adolescents (that were published in 2022) into the Slovenian language (Kastelic et al., under review (b)). During the Covid-19 pandemic, we conducted a systematic review that showed children were significantly less physically active during the Covid-19 pandemic (Povšič et al., 2022). We also conducted an empirical study that showed the adverse impact of changed school environments (online schooling) during Covid-19 on 24-hour movement behaviours among students (Starbek et al., 2022). With these studies we contributed to the understanding of changed environments during crisis (i.e., Covid-19) on movement behaviours that are important mediators in the relationship between built environment and well-being (Kastelic et al., 2022a).

In another study related to reducing sedentary behaviour, we investigated the impact of active workstations (cycle and treadmill desks) on work performance and cognitive function as interventions. Through a meta-analysis of 18 studies, it was found that both interventions led to a reduction in typing speed, and typing errors increased during cycling interventions. However, there was no significant effect on selective attention tests, and recall ability improved. The study concludes that cycle and treadmill desks do affect work performance, but most likely not due to the decrease in cognitive function. Further research is needed to determine whether the decrease in work performance is acceptable,

considering the overall positive effects of implementing beyond the state-of-the-art active workstations in office settings (Podrekar et al., 2020b).

A similar article assessed the impact of cycle and treadmill desks on energy expenditure, cardiovascular indicators, and biochemical markers among sedentary workers. By analysing 22 studies, the study found that these desks led to significant increases in energy expenditure and heart rate, while reducing blood glucose and insulin levels. The study concludes that cycle and treadmill desks, which represent beyond state-of-the-art office furniture, can be beneficial in enhancing energy expenditure for sedentary workers, potentially mitigating the adverse effects of prolonged sitting at work (Podrekar et al., 2021). Such solutions might also mitigate musculoskeletal issues among office workers (Kastelic et al., 2018).

As the field of physical activity and sedentary behaviour for health recently evolved into studying movement behaviours across the entire 24-h day (in combination), we developed and validated one of the first questionnaires (Daily Activity Behaviours Questionnaire) of its kind (Kastelic et al., 2022b; Kastelic et al., 2023; Kastelic & Šarabon, under review (a)). We also contributed to the measurement of 24-h movement behaviours using activity monitors (Kastelic et al., 2021a), and using traditional state-of-the-art approach (Kastelic & Šarabon, 2018). Assessing and studying movement behaviours in an integrated fashion presents research that goes beyond the state-of-the-art. Our empirical studies on 24-h movement behaviours and health confirmed such an approach is superior to the traditional approach of studying and promoting movement behaviours in isolation (Kastelic, et al., 2021b; Kastelic et al., under review (c); Kastelic et al., under review (d)). Future studies exploring the impact of the built environment on health and well-being should consider 24-h movement behaviours (in combination) as a mediating factor.

Overall, our research makes a meaningful contribution to enhancing interior space quality across various dimensions. The studies we have undertaken encompass various focal points, including ICT, ergonomics, aesthetics, and human stress factors. With that, we offer a comprehensive body of evidence that provides insight into optimal practices in interior design for human wellbeing.

Sustainability of the research field assured at InnoRenew CoE

Over the duration of the InnoRenew CoE project, the broad implementation of the research fields at the partner organisations have remained relatively similar, but with increased focus on specific areas, such as wood and fire relations at ZAG, or digital monitoring of cultural heritage objects and indoor environments (ZVKDS, NIJZ). At InnoRenew CoE itself, the fields of research have remained well aligned with the original goals, but new directions have arisen both in response to demand (i.e., industrial interest, government funding) and breakthrough discoveries which have led to developments like the Engineered Living Materials lab in response to a successful ERC grant.

To maintain the level of research, funding opportunities are actively sought through partnerships with companies, forming consortia and applying for tenders, and working with students as they pursue their advanced degrees.

Overall, InnoRenew CoE has submitted 133 proposals to international funding opportunities, 152 to national opportunities, and has engaged in over 300 partnerships with companies. The success rate of international proposals is 21 %, national proposals 40%. Successful proposals resulted in over 13,4 million EUR additional funding for InnoRenew CoE.

New avenues of additional funding are frequently explored as well. Long term relationships with funders are a critical aspect of InnoRenew CoE's success. These relationships are developed through active engagement with funders, contributing to policy development, and advocating for funding for the field. InnoRenew CoE has been part of many policy related initiatives, including the H2020 WoodCircus project (Grant # 820892) which formulated policy recommendations for implementing circular economy activities in the wood sector. In addition, InnoRenew CoE has contributed to policy papers related to healthy and dignified living for older adults, wood use in construction, etc. An important achievement for InnoRenew CoE and Slovenia is their role in the European Wood Policy Platform initiative (woodPoP), which is implemented by the ministries of the European Union member states under the joint leadership of Austria and Finland. woodPoP is a multilateral forum for policy making, exchange of knowledge and experience between public and private forest-based sector actors at national and regional level to share best practices and an opportunity to coordinate approaches in developing policy solutions to increase sustainable production and consumption of wood and its contribution to an innovative, circular bioeconomy. Slovenia took over the leadership of the Technical Working Group for Education and Vocational Training in the woodPoP initiative, whose primary tasks are to foster good practice exchange among the partner countries, and facilitate policy preparation that would positively influence attractiveness and quality of these fields for the benefit of forest-based sector. The work is led by the Ministry of Economy, Tourism and Sport, who hired InnoRenew CoE to implement the role. With this role we are placing

Slovenia at least alongside, if not at the head of, countries that use wood to achieve success both in the economic field and in social development, while at the same time mitigating the climate crisis.

Funding opportunities further in the future are always considered as well. Opportunities to contribute to the development of the New European Bauhaus and other sustainable and resilient building initiatives are considered positive for the future sustainability and development of the organisation and its research programme.

Although it is difficult to form definitive lines between the areas of many research proposals due to their interdisciplinary nature, many of the successful publicly funded projects are identified in each section below.

3.1 Materials

The materials research has garnered significant success. Its impact has led to a recent reorganisation of research groups at InnoRenew CoE and the formulation of a Materials research group focused on designing, developing, and testing a new generation of functional bio-based materials. The table below highlights several of the most impactful grants that have driven the success of the group.

Table 1 Highlighted projects categorised under materials.

2018-2020	Multi-spec “Spectroscopy and multivariate data analysis for quality control of modified wood”	BI-IT/18-20-007; Funded by ARRS Slovenia	More Info
2018-2020	“Protection of bronze monuments in the changing environment” J7-9404 (C). Funded by ARRS Slovenia	J7-9404 (C); Funded by ARRS Slovenia	More Info
2019-2022	CLICKdesign “Delivering fingertip knowledge to enable service life performance specification of wood”	ERA-NET Cofund ForestValue	More Info Project site
2020-2022	HYGRO-WOOD “Understanding hygroscopic properties of wood through multiscale modelling”	BI-LT/20-22-002; Funded by ARRS Slovenia	More Info
2021-2022	NOMOREFIRE “Novel modification treatments to improve wood resistance against fire”	BI-FR21-22-PROTEUS-006; Funded by ARRS Slovenia, PHC Proteus	More Info

2021-2023	BIO4CARE "Green synthesis of sustainable bio-sourced multifunctional ingredient for skin care applications"	GA# 101023389 H2020-MSCA-IF-2020	More Info Project Site
2021-2024	OLEAF4VALUE "Olive leaf multi-product cascade-based biorefinery: From an under-used biomass in the primary sector to tailor-made solutions for high added-value international market applications"	GA# 101023256; H2020 – BBI	More Info Project Site
2021	Esterification of Scots pine wood samples with fatty acids PR-39/2020	Industrial Funding	
2022-2026	NewWave "Building a sustainable & circular economy through innovative, bio-based manufacturing lines"	GA# 101058369; Horizon Europe	More Info Project Site
2022-2027	ARCHI-SKIN "Bioinspired living skin for architecture"	GA# 101044468; ERC CoG 2021	More Info Project Site
2023-2026	DIAMONDS "DIAgnostics and Mechanical tests Of aged adhesive layers used in joiNts of wooden structureS"	N2-0280 Funded by ARRS Slovenia	More Info
2023-2025	MULTI-WOOD "Multi-functionalization of wood with bio-based approach"	GA# 101067636; H2020-MSCA-IF-2021	Details forthcoming Info on Cordis

3.2 Business support

Research in support of businesses – and business system research designed to optimise business activities – are done in collaboration with companies through public funding and through direct contracting with companies. Occasionally, business support work is conducted through policy-oriented activities, such as suggestion how certain policies should be implemented to ensure the social and environmental goals can be reached as well as the

economic goals. Table 2 lists selected funded projects that highlight the range of activities conducted in support of businesses.

Table 2 Business support related projects carried out at InnoRenew CoE

2019-2022	CLICKdesign "Delivering fingertip knowledge to enable service life performance specification of wood" ERA-NET Cofund ForestValue	ERA-NET Cofund ForestValue	More Info Project site
2021-2023	Economic, environmental and social aspects of wood processing and its use and carbon sequestration	V4-2124; Funded by ARRS Slovenia and Ministry of Economic Development and Technology, Slovenia	More Info
2018-2021	WoodCircus, "Underpinning the vital role of the forest-based sector in the Circular Bioeconomy"	GA# 820892; Funded through H2020	More Info Project Site
2019-2023	Pharaon, "Pilots for Healthy Active Ageing"	GA# 857188; Funded through H2020	More Info Project Site
2022-2025	WoodLCC "Enhanced Life-Cycle-Costing in wood construction by novel methods for service life planning"	ERA-NET Cofund ForestValue	More Info

3.3 ICT

ICT research at InnoRenew CoE is focused on industrial optimisation, wireless sensor networks (WSNs), and increasing technology adoption by building designers and users. Table 3 lists a selection of the most relevant projects on these subjects.

Table 3 Projects related to ICT research.

2019-2022	"Optimisation for sustainable supply chains"	N1-0093; Funded by ARRS Slovenia	More Info
2019-2023	Pharaon, "Pilots for Healthy Active Ageing"	GA# 857188; Funded through H2020	More Info Project Site

2020-2022	Optimization problems of the residual biomass value chain"	BI-AT/20-21-014; Funded by ARRS Slovenia	More Info
2020-2023	"Autonomic edge computing for air quality monitoring"	J2-2504; Funded by ARRS Slovenia	More Info
2021-2023	Economic, environmental and social aspects of wood processing and its use and carbon sequestration".	V4-2124; Funded by ARRS Slovenia and Ministry of Economic Development and Technology, Slovenia	More Info
2021-2023	"Graph Theory and Combinatorial Scientific Computing"	N2-0171; Funded by ARRS Slovenia	More Info
2021-2023	"Optimization and fault forecasting in port logistics processes using artificial intelligence, process mining and operations research"	BI-HU/21-22-010; Funded by ARRS Slovenia	More Info
2021-2023	"Development of multi-objective optimisation algorithms for the design of buildings"	BI-HU/21-22-004 Funded by ARRS Slovenia	More Info
2021-2024	"Reverse supply chain of residual wood biomass"	N1-0223 Funded by ARRS Slovenia	More Info
2022-2024	"Decentralized communities for building monitoring"	BI-US/22-24-153 Funded by ARRS Slovenia	More Info

3.4 Sustainable buildings

Most InnoRenew CoE projects are linked to sustainable buildings. By design, the research work at InnoRenew CoE contributes to sustainable design, construction, use, and end-of-life for buildings. Table 4 lists a subset of the projects most directly on the topic of sustainable construction.

Table 4 Projects related to sustainable buildings.

2018-2020	E-REFIT "Strategies for improvement of energy efficiency of residential buildings through retrofitting"	BI/BA-19-20-030; Funded by ARRS Slovenia	More Info
2018-2021	Archi-BIO "Perception and performance assessment in bio-based architecture"	BI/US-20-054; Funded by ARRS Slovenia	More Info
2019-2022	CLICKdesign "Delivering fingertip knowledge to enable service life performance specification of wood"	ERA-NET Cofund ForestValue	More Info Project site
2020-2023	"Autonomic edge computing for air quality monitoring"	J2-2504; Funded by ARRS Slovenia	More Info
2021-2023	"Economic, environmental and social aspects of wood processing and its use and carbon sequestration"	V4-2124; Funded by ARRS Slovenia and Ministry of Economic Development and Technology, Slovenia	More Info
2021-2023	"Development of multi-objective optimisation algorithms for the design of buildings"	BI-HU/21-22-004 Funded by ARRS Slovenia	More Info
2022-2024	"Decentralized communities for building monitoring"	BI-US/22-24-153 Funded by ARRS Slovenia	More Info
2022-2025	WoodLCC "Enhanced Life-Cycle-Costing in wood construction by novel methods for service life planning".	ERA-NET Cofund ForestValue	More Info
2022-2025	SEAFARER "Protein-based adhesive for high-performance indoor timber structures"	J4-4546 Funded by ARRS Slovenia	More Info
2022-2027	ARCHI-SKIN "Bioinspired living skin for architecture"	GA# 101044468; ERC CoG 2021	More Info Project Site

Conclusion

The InnoRenew project set out to change the research landscape in Slovenia, advance the state-of-the-art in its fields of interest, and become a driver of change in sustainable construction by creating, outfitting, and staffing a new research centre on Slovenia's coast. By design, the work conducted by InnoRenew CoE contributed to the UN's Sustainable Development Goals. While emphasis was given to SDGs 11, 9, and 3, many other SDGs were highly relevant to the InnoRenew CoE (Figure 12).

Figure 12 Sustainable Development Goals contributed to under each research category.

The ongoing and future work of InnoRenew CoE will continue to contribute to the SDGs, while also focusing on work in support of the European Green Deal and the New European Bauhaus. In continuing this work – in collaboration with other research partners, governments, and companies – we look forward to advancing the economic, environmental, and social wellbeing of Slovenia, the EU, and the globe.

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