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BEEYONDERS: Breakthrough Technologies For A Human-Centric, Digitalized And Automated Construction Sector: Challenges And Impact Analysis

Jimenez Fernandez, Jose Carlos[1*], Alonso-Cepeda, Antonio[2]
[1] TECNALIA, Basque Research and Technology Alliance (BRTA), Bizkaia Science and Technology Park Astondo bidea Edificio 700, E-48160 Derio, Spain. Email: josecarlos.jimenez@tecnalia.com
[2] ACCIONA Construction SA, Technology and Innovation Direction, Construction Technology Centre – Valportillo Segunda 8, 28108 Alcobendas, Spain. Email: antonio.alonso.cepeda@acciona.com

Abstract: *The construction sector is currently facing unprecedented global challenges, including labour shortages, workforce aging, low productivity, and increasing demands for sustainability and safety. These issues are similar to those encountered in Japan, where the preparation for the Tokyo Olympic Games prompted a national shift toward automation and digitalization under the "Smart Construction" initiative a technology-driven approach emphasizing automation, robotics, and artificial intelligence.*
The European Union's demographic trends and labour market evolution suggest that the construction sector in Europe is approaching a comparable situation. Consequently, the European construction industry must follow a similar paradigm shift, integrating advanced technologies to stay competitive. Inspired by Japan's experience, the BEEYONDERS research project has been established to address these major sectoral challenges.
BEEYONDERS has developed and validated a portfolio of breakthrough technologies in six key domains: autonomous vehicles, additive manufacturing, real-time safety and monitoring systems, digital twin platforms, human-robot collaboration and AI-based decision support. These innovations have been tested and demonstrated in six diverse use cases, one of which highlights European-Japanese collaboration—underlining the vital role of international cooperation in fostering a sustainable and competitive construction sector.
This paper presents a comprehensive analysis of the challenges addressed and results achieved by BEEYONDERS, focusing on social impact, economic feasibility, and environmental benefits. By approaching the transformation of the construction sector from multiple complementary perspectives—technical innovation, social inclusion, economic viability, and environmental sustainability—the project aims to demonstrate how digitalization and smart technologies can profoundly reshape the future of the construction industry, ensuring resilience and long-term success.
Keywords: *Smart Construction, Breakthrough Technologies, International Cooperation, Impact Analysis.*

1. INTRODUCTION

The construction industry, a cornerstone of economic development, faces multifaceted challenges in the 21st century. These include workforce shortages, aging labour demographics, declining productivity, and rising demands for sustainability, safety, and digital integration. BEEYONDERS (Breakthrough European tEchnologies Yielding cOnstruction sOvereignty, Diversity & Efficiency of ResourceS), a Horizon Europe research initiative, responds to these challenges by pioneering a portfolio of breakthrough technologies (BTs) aimed at reshaping the sector. This paper presents the motivation, methodology, technologies, use cases, and impact analysis strategy of the BEEYONDERS project.
The construction sector is historically characterized by slow rates of digital adoption and fragmented innovation. Despite being one of the largest employers and a significant contributor to GDP across the world, the industry has lagged behind others like manufacturing and logistics in embracing Industry 4.0 paradigms. This is compounded by structural inefficiencies, safety hazards, high material waste, and an over-reliance on manual labour. The convergence of environmental mandates, societal expectations for inclusive and safe workplaces, and economic imperatives for greater efficiency makes innovation not just desirable but essential [1].
Recognizing this, the European Commission's Horizon Europe programme launched specific calls to promote a transformation in construction [2]. BEEYONDERS emerged from this vision with the ambition to enable European companies, researchers, and policymakers to drive change from within the continent—fostering technological sovereignty while promoting sustainability and social equity. At its heart, BEEYONDERS

embraces a human-centric approach, ensuring that automation and digitalization enhance—not replace—the role of workers, with a particular emphasis on inclusivity and well-being.

Moreover, BEEYONDERS stands out for its holistic, systems-level approach. It integrates technological development, field demonstration, stakeholder engagement, and policy alignment within a cohesive framework. The technologies span diverse domains—from robotics and additive manufacturing (AM) to AI-driven decision support and digital twins—reflecting the sector's multifaceted nature. Through its six real-world use cases and international collaboration with Japan, BEEYONDERS aims to demonstrate not only technical feasibility but also societal relevance and market readiness [3].

This paper aims to provide a comprehensive overview of the BEEYONDERS project, structured around its strategic objectives, technical innovations, demonstration results, and socio-environmental impacts. In doing so, it contributes to the broader discourse on the future of construction and the pivotal role of European R&D in shaping a smarter, safer, and more sustainable built environment.

2. Context and Motivation

Japan's response to similar challenges, especially in preparation for the Tokyo 2020 Olympic Games, provides a compelling precedent. Through the "Smart Construction" initiative, Japan deployed automation, robotics, and AI to overcome labour shortages and improve productivity. The initiative was driven by the urgent need to deliver large-scale infrastructure projects within a compressed timeline, with a reducing labour force and exigent safety requirements [4]. Technologies such as autonomous bulldozers, drone-based mapping, and AI-powered construction management systems were rapidly implemented and scaled across the country [5].

The European construction sector now confronts a comparable situation. Demographic trends, such as declining birth rates and an aging workforce, are exerting pressure on the availability of skilled labour. Meanwhile, the green and digital transitions are placing new demands on the sector to innovate. Regulatory frameworks increasingly prioritize low-carbon solutions, circular material usage, and occupational health. Public and private clients alike expect higher standards in project delivery—faster, cleaner, and safer.

Adding to the complexity, the construction sector is inherently fragmented, with a predominance of small and medium-sized enterprises (SMEs) that often lack the resources to invest in high-risk innovation or advanced digital technologies. Without a coordinated effort, the sector risks falling behind global competitors and becoming increasingly dependent on imported technologies developed in the US or China. [6].

The BEEYONDERS project is Europe's strategic answer to these multifaceted challenges [7]. By leveraging its strengths in research, policy coordination, and industry collaboration, Europe can create a self-sustaining ecosystem of innovation in construction. BEEYONDERS proposes to lead this transformation by focusing not only on technological development but also on human-centered design [8], workforce empowerment, environmental stewardship, and cross-border collaboration.

Ultimately, the motivation behind BEEYONDERS is to demonstrate that construction, often viewed as a traditional and conservative sector, can become a frontier for digital and green innovation—where humans and machines work safely and efficiently together, where inclusivity and well-being are embedded by design, and where Europe can lead on the global stage through sovereignty, sustainability, and smart solutions.

3. Objectives of the BEEYONDERS Project

The BEEYONDERS project is guided by a set of ten strategic objectives that together define its scope, ambition, and methodology. These objectives are designed to address the most pressing challenges of the construction sector in Europe—namely, technological dependency, labour shortages, inefficiencies in project delivery, environmental impact, and worker safety and well-being. Each objective is supported by Key Performance Indicators (KPIs), enabling clear progress tracking and measurable outcomes [9]. These objectives are the following:

O1: Set up the performance requirements for BEEYONDERS – This objective ensures a strong foundation by identifying the requirements for technologies and solutions. It addresses technical, environmental, economic, and social expectations and establishes a framework for gender-sensitive design, lifecycle cost analysis (LCA/LCC), and worker safety.

O2: Define and set up testing protocols at TRL 4 and 5, and demonstration plan at TRL6 – The project transitions technologies from laboratory environment validation (TRL4) to relevant environments (TRL5) and finally to on-site demonstration (TRL6). These structured stages are critical for ensuring safety, repeatability, and relevance in real construction contexts.

O3: Develop, test, and demonstrate Autonomous & Collaborative Robotics solutions – These robotics solutions aim to automate hazardous, repetitive, or high-precision tasks in construction. Examples include a wheel loader that autonomously excavates in tunnels, drone-ground coordination for roadworks, and autonomous systems for inspection. Demonstrators show reduced fuel use, improved accuracy, and increased task speed, thereby addressing safety, sustainability, and productivity simultaneously.

O4: Develop, test and demonstrate environmentally friendly AM solutions – BEEYONDERS advances 3D concrete printing techniques adapted for coastal and subsea construction. These reduce CO_2 emissions through material optimization and enable the creation of reef-supportive structures. Technologies developed have been validated in maritime construction and EU-Japan cooperation use cases.

O5: Develop, test and demonstrate a Digital Twin with Data Fusion and AI integration – A centralized digital twin platform aggregates multi-source data from machines, wearables, sensors, and environment to visualize and analyse performance in real time. AI modules offer predictive maintenance, scheduling optimization, and risk identification. These technologies are essential for the project's ambition to digitize entire construction processes.

O6: Implement and evaluate worker-centric technologies – The project develops technologies not only for automation but also for improving human experiences. These include wearables for posture and fatigue monitoring, exoskeletons for reducing musculoskeletal strain, and user interfaces co-designed with workers. Evaluations include inclusiveness indicators such as gender fit, usability for older workers, and compatibility with disability needs.

O7: Develop training and learning resources – Training modules ensure that BT adoption is inclusive and sustainable. VR simulations, digital guides, and modular learning content are developed for workers, engineers, and vocational institutions. These resources support upskilling and long-term workforce development across Europe.

O8: Perform standardization activities – To ensure scalability, technologies are aligned with European and international standards.

O9: Develop international cooperation with Japan – A dedicated use case in maritime construction integrates insights from Japan's "Smart Construction" initiative. Joint workshops, technology exchanges, and demonstration alignment enhance mutual learning and global interoperability. This also strengthens Europe's positioning in global markets.

O10: Design and implement Market analysis, Dissemination and Exploitation Plans – Business models are created to ensure future exploitation of BEEYONDERS innovations. This includes IP management strategies, stakeholder engagement, commercialization planning, and clustering with other EU projects.

Together, these objectives position BEEYONDERS as a comprehensive, multidimensional initiative capable of reshaping the future of construction in Europe and beyond. By addressing the full innovation cycle—from requirements to market impact—and considering both human and technological factors, the project offers a replicable model for systemic transformation.

4. Methodological Approach

A. Common Framework

The BEEYONDERS methodology is built on a structured and integrative framework that spans the full innovation lifecycle—from requirements definition to demonstration and impact assessment. This approach is designed to accommodate the complex, multi-stakeholder, and multidisciplinary nature of the construction industry while ensuring technical robustness, replicability, and social acceptability.

The project' common methodological workflow is divided into the following sequential phases:

- Requirements definition and system modelling: Early in the project, system requirements were captured through stakeholder consultations and surveys involving partners from across the value chain.
- Technology development and integration: Technologies are developed within specialized technical work packages and aligned with the system requirements. Each technology is designed with scalability and interoperability in mind. Components are validated progressively at TRL 4 (laboratory), TRL 5 (relevant

environment), and finally integrated into demonstration sites at TRL 6. This approach is explained in detail in the next subsection.

- Use case planning and deployment: Six use cases were selected to represent the diversity of real-world construction environments, including tunnel, road, building, maritime, and maintenance contexts [3], [9].
- Common KPI framework and Impact Metrics: A key methodological innovation in BEEYONDERS is the establishment of a harmonized KPI framework for all use cases. KPIs span four dimensions—technical, environmental, social, and economic—and are used both to monitor technologies performance and to compare scenarios. The metrics have been defined and are applied through templates and dashboards standardized across the consortium [9].
- Cross-use case coordination and feedback loops: Use cases work package is designed to ensure cross-case comparability through a shared methodology. Lessons learned in each use case are fed back into technology adaptation and further development cycles. This iterative refinement process ensures that innovations are not just viable in theory but proven under operational constraints [9].
- Digital Twin and AI-enabled monitoring: A central digital twin platform, integrates data streams from sensors, robots, and wearables. It supports real-time visualization and predictive analytics, enabling continuous monitoring of safety, productivity, and environmental metrics.
- Validation and Impact Assessment: Final validation synthesizes all data collected during demonstrations. Impact assessments are conducted based on improvements against baseline KPIs. These assessments guide future standardization, exploitation, and scalability efforts [9].

This methodological architecture ensures traceability, repeatability, and scientific rigor, while simultaneously allowing enough flexibility to address the diverse challenges faced by construction stakeholders in Europe and beyond.

B. R&D Methodology

The R&D methodology designed for BEEYONDERS is a continuous feedback loop between design, development, and validation-demonstration where design is, however, at the beginning of the whole process.

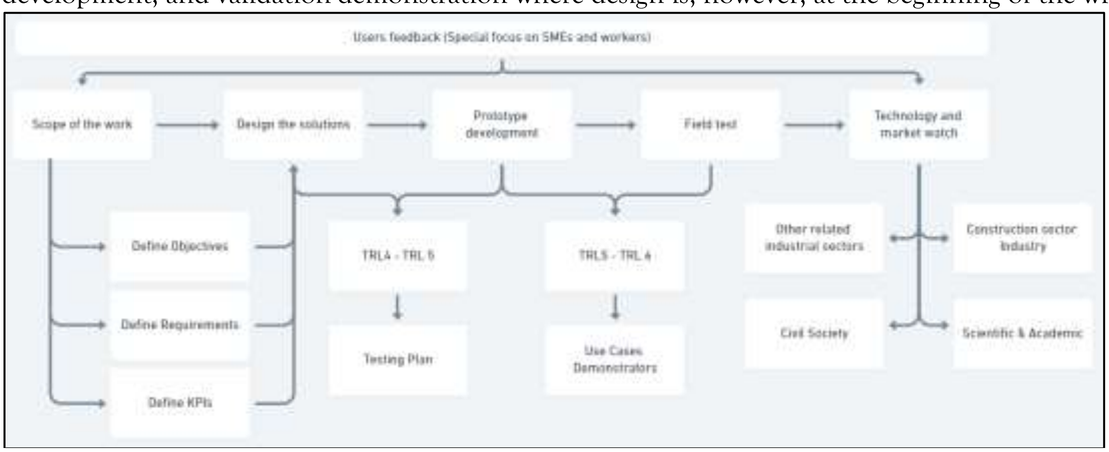

Fig. 1. BEEYONDERS' R&D methodology and strategy scheme.

Design is understood as a qualitative and quantitative set of principles that will be breakdown in requirements, objectives and, finally, Key Performance Indicators (KPIs) referring to Human-centric principles, Automation of the construction site, Technology integration (from other industries and in BEEYONDERS) in construction, Resource efficiency, reduction of waste, reduction of embodied CO2 emissions, Safety, wellbeing, and prevention, Technical performance, Non-technical performance (legal, standards, etc.), Economic performance and Competitiveness with non-EU competing solutions.

The KPIs have been set at the beginning of the project to guide technological and non-technological performance targets for development of the individual solutions and for their integration as a whole and to blueprint the test and validation program to iteratively validate the results at different stages and TRLs of the project. Design is set at the beginning of the project, but, while the main principles and KPIs will remain untouched, these will be revisited, nurtured and enhanced with new relevant information, to keep pace with the progress of reality, which will affect the all parameters as they evolve in time (e.g. change in external requirements and conditions of any type: markets, legal, technological, etc.). The market and technology watch performed in Communication, Standardization, Dissemination and Exploitation tasks are key to support this evolution.

Development starts at TRL 4 with the technological work packages, and takes the solutions and their integration to TRL5, evolving to prototypes, under the guiding KPIs, and with the feedback of testing at the level of TRLs 4 (laboratory environment) and 5 (relevant Digital Twin -integration environment). The prototypes and the whole BEEYONDERS integrated solution as applied to the different use cases are, at the final stage, reaching TRL6, further fine-tuned and adjusted with the inputs from the validation campaign in the case studies. As a mean of assuring the successful achievement of target TRL6, the WPs time distribution (Gantt) has been designed in order to permit an overlap between the beginning of the technical developments with the testing stage in the laboratory scale, and starting the case studies approximately at the midterm of the technological work packages in order to allow a further iteration of tuning these technologies while these are initially deployed on the case studies.

Validation-demonstration is organized in two main segments. The 1st segment occur within the definition of a Testing Plan for the solutions and their integration, according to the KPIs resulting from the design, i.e. the detailed planning and configuration of the tests needed to evaluate the performance of the solutions at two stages of development: a) laboratory scale validation of the individual solutions and of their conceptual integration at TRLs 4, and b) validation of their solutions and their integration in relevant environment (TRL 5), this is, at a scale where the actual prototypes are working together in an integrated manner, being the Digital Twin the container of such integration, leaving the laboratory to work in test facilities and real interconnection at a level prior to field case studies. The 2nd segment of validation will follow the same main scheme in the use cases work package, beginning with the planning of the validation campaigns in each of the case studies and performing the validation at real scale to reach TRL6.

This R&D methodology explained above applies to all the BEEYONDERS technologies that belong to the objectives of the project and ensures an iterative design & evaluation loop for a more optimised result.

C. Technical approach per technology

This section outlines the specific technical approaches adopted for each key technology developed within the project, detailing their architecture, integration strategy, and role in enabling advanced, resilient, and scalable solutions for real-world construction scenarios.

Autonomous Ground Vehicles

A layered architecture has been built with an interface for algorithm modules and designed to modify and contribute with new code. To build the map, the robot makes use of the data gathered to compute its own movement and data collected from new advanced sensors integrated into the machines to increase its level of autonomous navigation. In this approach, the map will be represented as a graph where nodes represent positions along the trajectory followed by the robot and the edges encode spatial relations between nodes or absolute information associated to those positions. The system will detect changes on the environment that are not represented on the map and update the map. The machines should operate in collaboration without human intervention while performing near a human-equivalent workload, for this purpose a high-level module for decision-making that coordinate and schedule the task between machines and learn about the process using reinforcement learning approach using as rewards parameters that measures the efficiency and productivity is developed [11].

Aerial Autonomous Vehicles

The design and development of the aerial autonomous vehicles has implemented a user-centered design process all along the project duration. Two main areas that cover the case studies in which aerial robots are employed are split as indoor and outdoor. The indoor system will reach the autonomous navigation in a GNSS-denied environment, using a 3D LIDAR for the autonomous navigation, which has provided the required accuracy in the robot localization and the safety needed for navigating in cluttered environments. LIDAR sensor measurements have been fused with the onboard inertial sensors to improve the stability of the localization algorithm, and the 3D environment reconstruction has been based on the sensor data acquired during the autonomous flights. The outdoor system, GNSS-based localization solutions fused with inertial sensors and suitable sensors for obstacle detection and avoidance are needed, as per developing the collaborative performance with other devices proposed.

Additive Manufacturing

3DCP robotic device has manufactured a prototype of caisson and a 3D printed reef attached to one of the vertical parament. Pre-design has been done and requirements on materials (structural or biodiversity-promotive) have been obtained. From an extensive IoT framework during manufacturing of the printing material, manufacturing methods have been compared and adjustments on materials been derived for materials development. Materials recipes for manufacturing of the caisson itself, included promotion of bio-marine life elements are developed and tested at laboratory scale. LCA, cost and construction duration benchmark have been followed. Materials performances, structural integrity and biodiversity promoting function are validated through the case study integrated into the Digital Twin.

Exoskeleton

The design and development of the Exoskeleton has been applied to a User-Centered Design approach iteratively to optimize the resultant device and produce a design that fully meets the stakeholders' demands. It has been comprised a mechatronic design, mechanical structure, and wearable sensors. In addition to the hardware, a dynamically stable assistive multi-layer control algorithm has been developed. This control architecture has three levels: low-level motor control, mid-level for selection of ad-hoc the assistive strategy and a high level for recognition of the worker activity. These developments are subdivided into the control strategies to provide specific assistance during walking, holding, lifting, lowering, load-carrying, pulling, and pushing, and an online activity recognition algorithm. It will be evaluated the performance, comfort, and ergonomic aspects, and together with the continuous iterative cycling between the developments and testing phases with the full involvement of the end users.

Smart Wearables

As the Exoskeleton, the Smart Wearables have followed a similar research approach. Technological components have been developed and tested in laboratory environment based on the requirements from project's specifications. Also, individual components have been tested before integrated together to the Digital Twin. Some of the technical component's development have included machine learning which needs a data collection for training the specific component outcomes. The solutions have been tested in different case studies, where technical and usability aspects have been evaluated during this phase. Validation will be carried out by collecting technical data of performance as well as user experience interviews to the case studies participants. The feedback generated during the case studies have fed the technology adaptation due to different feasibility or viability requirements learned in evaluation.

Human – Robot Collaboration

An agent-based model has been developed as support tool for the activities in the case studies where coexistence and cooperation between machines and human is planned. The system aims to identify possible risks and conflicts by simulating both human operators and machines tasks in terms of multiple parameters such as motion in the worksite or sequence of sub-tasks. Agent-based model has been fed with the algorithm and behaviour patterns developed for determining the tasks and the movements of the robotic machines, also considering the perception system on board of each machine for collision avoidance. An accurate description of the activities will complete the framework of information necessary for the development of the agent-based model.

Digital Twin

The results obtained in BEEYONDERS have been centralised and assessed in the Digital Twin environment. A fully integrated Digital Twin must be specified and implemented and stored in a dedicated database. The initial Digital Twin model is built, through specific data importer (static data importation layer), from the BIM models provided by the conception phases of the project, and from initial planification data. This model is connected to a set of "Input services", that has produced the specific indicators based on the KPIs defined [10]. All the "active" parts of the construction site (workers, equipment, machines, robots, drones) have provided, through sensors, a big amount of information (position, orientation, cloud points, distances, …). All this information has been plugged to the Digital Twin and treated by dedicated "Output services".

D. Ambition of Breakthrough Technologies Developed

The BEEYONDERS project has designed, developed, and validated a diverse portfolio of BTs that address specific needs in the construction sector. These innovations extend the state of the art by enabling interoperable, human-centric, and environmentally sustainable solutions. Below is a summary of each technology area, highlighting current limitations and the ambition that BEEYONDERS aims to achieve:

Autonomous Ground Vehicles

Autonomous ground vehicles play a pivotal role in improving efficiency and safety in harsh construction environments. BEEYONDERS addresses the limitations of traditional perception and mapping methods by enabling real-time 3D mapping through collaborative sensor networks mounted on heavy machines. Reinforcement learning techniques are employed to endow these machines with cognitive capabilities, allowing them to recognize patterns in unstructured terrain and adapt task execution strategies dynamically. In road maintenance scenarios, these machines autonomously identify potholes, avoid obstacles, and coordinate with aerial platforms for optimized task planning [11].

Autonomous Aerial Vehicles

To overcome the limitations of manual drone piloting, BEEYONDERS develops GPS-free navigation systems using SLAM algorithms optimized for tunnel and building environments. The aerial platforms also employ long-range sensors and edge computing to support continuous inspection of infrastructure such as linear infrastructures as roads or railways lines. A key innovation is the integration of aerial data into object-oriented digital models. These models are dynamically updated and linked to the digital twin, enabling stakeholders to visualize structural evolution and correlate it with other operational parameters [12].

Additive Manufacturing

BEEYONDERS redefines the application of 3D concrete printing by focusing on ecological performance and formwork elimination. IoT devices embedded in the printing hardware monitor parameters such as temperature, humidity, and print layer consistency. AI models optimize the cementitious mixture based on real-time sensor feedback to ensure mechanical reliability. The project's Additive Manufacturing demonstrators focus on maritime infrastructure—specifically, caisson production and artificial reefs. By embedding habitat-forming geometries into caissons, BEEYONDERS transforms structural components into eco-functional assets that promote marine biodiversity [13].

Advanced Wearables

Wearable technologies in BEEYONDERS are tailored to capture comprehensive data on worker posture, motion, and environmental exposure. The wearables use inertial measurement units (IMUs) and wireless transmission protocols to deliver real-time feedback to supervisors and safety systems. These sensors are embedded in standard personal protective equipment (PPE) such as vests and belts to avoid interference with worker mobility. Machine learning models analyse movement patterns and issue warnings when fatigue or hazardous posture is detected, improving long-term well-being and reducing injury rates [14], [15].

Exoskeletons

The exoskeleton developed in BEEYONDERS is a significant evolution from traditional assistive devices. It supports both the lower back and upper limbs in a coordinated manner, addressing multiple movement axes simultaneously. The system is enhanced with bioinspired sensors that interpret user intent through electromyographic (EMG) signals and motion patterns. Intelligent control units dynamically adjust the level of assistance based on task complexity and user behaviour. The exoskeleton is adaptable to different body types and incorporates safety shut-off mechanisms to prevent overexertion or misalignment [16], [17], [18].

Digital Twin Platform

BEEYONDERS' digital twin acts as the 'central nervous system' of the project, integrating all data streams from robots, wearables, and monitoring tools. The platform models the construction site in real time, visualizing worker KPIs, equipment performance, and environmental metrics. Advanced AI tools embedded in the twin provide predictive analytics—such as forecasting delays, identifying bottlenecks and performing H&S compliance checking employing data collected from the devices deployed on site, both workers PPEs and robotic solutions—and decision-support dashboards for site managers. The digital twin also supports training modules and remote supervision, reinforcing operational transparency and workforce engagement [19], [20].

DNHS, Neutrality and Circularity.

This line will be based on ensuring that project developments will respect do no significant harm (DNHS) principles. Technologies, processes and, eventually, material management will tend to CO_2 neutrality and resources circularity, applying LCA and LCC methodologies and/or other strategies, and justifying the benefit of applying these technologies [9].

5. Use Case Demonstrations

Six use cases across four countries (Spain, Italy, Finland, Netherlands) served as testbeds for technology validation:

- Tunnel construction (conventional explosives)
- Road construction
- Building construction
- Maritime construction
- Maritime construction (EU-Japan collaboration)
- Road maintenance

The data collected in each use case has been used to compare baseline workflows with BEEYONDERS technologies enhanced scenarios, supported by harmonized KPI measurements.

A. Use Case 1: Tunnel Construction

Santa Barbara Foundation Test Tunnel, Leon, Spain

Tunnel works, which are carried out in rocky terrain, often require explosives for their execution, being necessary to use specialized machinery such as jumbos. These types of works are one of the most dangerous ones in the construction sector, implying highest safety measures in the tunnel, including of course, the total absence of workers. The traditional way of executing this process is to use a jumbo to drill the excavation front to introduce explosives. Once the blasting has taken place, it is necessary to wait for the air extraction systems to eliminate the suspended particles and make the tunnel atmosphere breathable and transparent so that workers can enter. There is no possibility of working within the infrastructure if adequate safety conditions are not met. This fact supposes an unproductive waiting time around one hour, not negligible with respect to the total hours worked, even more, when several blasts must be carried out per day if working 24 hours a day.

BEEYONDERS proposes a solution to these unproductive waits through the demonstration in a use case of a test tunnel located in León (Spain), in which it is proposed to use autonomous and teleoperated robotics applied to two construction machinery vehicles, together with a drone. Immediately after the explosion and with an atmosphere without visibility (a cloud of dust), the drone will enter scanning the tunnel and obtaining a point cloud and the current state of the tunnel. The main indoor details of topology will be transmitted to the loader and dumper assembly, advancing these vehicles behind the autonomous drone avoiding all of them any kind of obstacles and generating an autonomous location and navigation without GPS signal. Once the place of the explosion has been reached (excavation front), they will carry out debris removal tasks, evacuating the material to the outside and repeating these tasks as many times as necessary while the atmosphere is unbreathable. A record of the progress of the vehicles and the status of the tunnel through the transmission of information from the machinery and drone to the Digital Twin and to specific Artificial Intelligence applications to control the progress of the work will be kept, getting a current state of the executed excavation tasks vs. the planned ones.

B. Use Case 2: Road Construction

L'Aquila, Italy

A use case is proposed for the construction of a road located in Italy. For this type of work, the phase that consumes more resources is earthworks, in which different types of construction machinery modify the terrain to adhere to what is planned in the execution project. Site managers must plan how these tasks will be carried out on site: machinery vehicles available, skilled workers, weather conditions, interference with other phases of the site, etc. Once this phase begins in each of the sections of the work, drivers are who make decisions regarding the tasks to be carried out and decide how they are going to drive these vehicles to move the terrain in the best possible way. Although they are experts, they will drive neither performing the best possible trajectories nor in the most efficient conduction mode, because they are human drivers and not optimized algorithms. We can translate this statement in two types of problems to improve. On the one hand, in terms of the subtasks to be carried out, choosing the correct order or the most optimal sequence of steps to achieve a certain configuration of the terrain. On the other hand, in relation to the fact that drivers will not carry out

these subtasks achieving the minimum routes to follow. These two circumstances cause more fuel to be consumed than is strictly necessary to achieve the construction objectives of the work, consequently emitting more CO_2. As we will see in Impact section, based on other parallel studies for other kind of vehicles, only controlling the way of driving, would be possible to achieve potential savings of 7% to 14% [21], [22].
The use of breakthrough technologies in this use case could solve the excess CO_2 emissions by implementing several technologies in a coordinated way. On the one hand, incorporating localization and autonomous navigation in vehicles, both terrestrial (construction machinery) and aerial (drones), and on the other hand, an optimized management of the work thanks to the Digital Twin with AI functionalities. Both sets of technologies, working in coordination, could get a current state-of-the-terrain situation and machinery on site by means of drones, transmitting data to the DT, which would contain information on the phases to be executed for that current state. After that, AI algorithms could select the priority tasks to work on, sending precise orders to the earthwork's machinery with optimal trajectories in terms of distance, and these machines, through autonomous and tele-operated navigation would carry out these tasks without the intervention of drivers. Once completed, drones would be ordered to assess the new situation, starting a new work cycle. Obstacle avoidance (human & machinery) will be considered while tasks are performed, deploying and validating the smart wearables into this scenario. A successfully carrying out and demonstrating of this way of working will mean a considerable reduction in CO_2 emissions in road works.

C. Use Case 3: Maritime Construction

Port of Gijón, Spain

Maritime works use-case has been selected because it represents a typology of construction works that has its own characteristics within construction. Its infrastructures are subject to demands that are totally different from the rest of the BEEYONDERS case studies because structural elements are subjected to the action of sea water chemical reactions and dynamic loads due to waves compared to the mostly static stresses of the rest of construction case studies. This must be strongly considered for its geometrically/structural design and the type of mortar to be developed to improve the behaviour of the final constructive element to be installed.
So far, ACCIONA has been manufacturing large concrete maritime caissons at the level of large-scale production in its Kugira's caissons manufacturing unit [23], [24] with great international success. In this context, the research for finding alternatives in the field of AM is proposed to implement solutions in the construction of marine infrastructures, which would mean facing a huge and completely innovative challenge. On the one hand, due to the lack of knowledge in the large-scale handling (meters) of robotized 3D printing systems with mortars. On the other hand, due to the lack of knowledge in the characterization and fundamentally absolute control of the physical-chemical properties that mortars must have to be used in AM processes, to achieve the rheological properties of workability and mechanical resistance. Finally, total control over the previous variables would allow the generation of new structurally optimized designs to fulfil their resistant and environmental function, while respecting marine biodiversity. For these reasons, a series of tests and demonstrators will be proposed in Spain (Port of Gijón) to research in the optimization of structural caisson designs, exploring other geometries that improve performance by reducing the amount of mortar that is wasted or used, thereby reducing CO_2 emissions. Additionally, the project has worked to achieve, through different AM technologies, surfaces that favor the settlement of marine biodiversity, generating shapes and textures on the outside of the caissons, which promote the growth of artificial reefs, which will have a very positive impact on the environment of seas. The results optimizing the properties of mortars to achieve the desired properties regardless of the variables of the input materials or environmental conditions have been demonstrated in a real plant at TRL 6, achieving the right mortar to be printed in any European location.

D. Use Case 4: Maritime Construction – Eu & Japan Collaboration

Port of Rotterdam, Dutch National test site

BEEYONDERS has worked in collaboration with the Japanese equipment manufacturer Giken Ltd to integrate into the Digital Twin deployed into the project a predictive geotechnical module for optimisation of resources (environmental & economical, mainly) for push-in pile construction system.
The data-rich nature of the Cone Penetration Test (CPT) has led to the recent proliferation of CPT-based pile design methods. This is largely because of the wide range of empirical correlations between CPT results and geotechnical parameters, as well as the detailed insights the CPT gives into the subsurface stratigraphy, particularly with respect to weak zones around the pile tip. However, while the CPT provides a wealth of

information in the vertical direction, data in the horizontal direction is sparse. This means that for developing site-wide ground models, the soil characteristics between CPT locations are subject to a large amount of uncertainty. In the context of pile installation, unforeseen changes in soil strength can lead to sudden delays and costs, highlighting the need for accurate and reliable ground models.
In this use case, the research focusses on using pile installation data to produce real-time updates to a CPT-based ground model, enabling the designer or contractor to make informed decisions over the course of installation work. As part of this, a new machine learning approach to ground modelling has been developed. The approach focusses on improving the resolution of ground models, particularly in terms of the detection of weak or strong layers which may substantially affect pile installation response.
The work has been completed using installation data from Giken machinery operating at two demo sites, one at a Japanese test site and the second at a Dutch National test site located in the Port of Rotterdam. This use case shows the potential of AI techniques, in the context of Digital Twins, for the optimisation of resources and time spent in a construction process. The data collected during this use case has then been used in the whole-life cycle assessment of the structure's behaviour.

E. Use Case 5: Building Construction

Helsinki Metropolitan Area in Southern Finland

Building construction sites are characterized by limited environments and locations in which construction tasks are predominantly vertical and not horizontal, as in the case of roads and tunnels, so their characteristics and the associated challenges are completely different from the above cases. Specifically, it can be said that there is a global increase in the density of workers and construction elements. Therefore, construction challenges will be related, on the one hand, to the safety of the workers, since the activities carried out and tools used for it, must be developed in a smaller space with a greater number of workers, increasing the possibility of accidents. On the other hand, higher construction complexity implies a better control of what is planned and executed. It is essential not to perform tasks incorrectly which later must be rebuilt, consequently generating a reduction in productivity and an increase in CO_2 emitted, due to repeating tasks, requires energy, and embedded CO_2, due to the need to manufacture and incorporate more materials than necessary [25], [26].
To meet these challenges, a building construction case study in Finland has been proposed in which two sets of BTs have been integrated. On one hand, those related to safety, which were related to wearables that workers wore, monitoring biometric and kinematic parameters. On the other hand, tasks related to measuring what has been executed, (acquisition of information on the degree of execution of the construction tasks and whether they have been carried out correctly). In the first case, two types were integrated: Exoskeletons and smart wearables. Exoskeletons were implemented to evaluate how safety conditions could be improved in workers of different ages and gender, to reduce their level of injuries at work, obtaining valuable information on how they could be prevented and how these systems helped to improve the wellbeing of workers. In the case of smart wearables, to measure occupational health and safety variables, to prevent accidents, whose initial symptoms, if they could have been measured, would have given enough information to avoid serious consequences. Testing different systems and knowing the feedback of workers, was essential to reduce the rate of accidents in construction. In the second case, the use of drones inside a building was planned and executed to capture the information of what had been carried out so far. In this system, as in the use-case of Tunnel, in which GPS signal was not available, was proposed to start working from the end of the workers' working hours, scanning the interior of each floor of the building to capture the information of the tasks carried out so far, flying autonomously. Once the flights were finished, the system was uploaded with the information to the DT, so that it could be compared with what was planned, making possible to know the degree of real progress of the workday by day and if there was any deviation from what was planned to combine this innovative approach in data acquisition with current BIM techniques.

F. Use Case 6: Road Maintenance

L'Aquila, Italy

Road maintenance is based on ensuring that the infrastructure remains in operation, with the minimum number of possible cuts and in the best service conditions for all users, at the lowest possible cost for the concessionaire. Under this premise, different types of elements on the road must pass periodic inspections. Some of them, several times a day, and others semi-annually or annually. At present, concession personnel who drives vehicles along the road, must check these points several times a day, in daytime and nighttime conditions, having to carry out maintenance inspections in adverse weather conditions, with safety concerns for both workers and road users [27]. It was proposed to use the technology of autonomous robotics (ground and aerial) to perform certain inspection tasks in road maintenance as:

- Check the retro reflectivity level of vertical traffic signals and check the status of horizontal ones [28]. It has been used a specifically designed four-wheel robot and a drone with an AI perception and analysis software).
- Check the vegetation status [29] right outside the road carriageway on the external border, measuring the growth and the type of growth, doing predictive analysis through an AI algorithm and using a robot/drone and its internal sensors and 3D maps to track the environment.

Based on previous tasks, prioritise interventions based on real needs, draw conclusions and provide input to the legislator to improve maintenance protocols. The autonomous robotic platform collaborating with autonomous aerial vehicles has demonstrated its capability to perform these tasks during operational road services without affecting infrastructure users.

6. Assessment Framework

The BEEYONDERS project has employed a robust and standardized assessment framework to evaluate the performance, impact, and replicability of its BTs across all six use cases. This framework has been critical for comparing the performance of traditional versus BT-enhanced workflows, ensuring traceability, and quantifying project success. The evaluation methodology has been based on a multi-dimensional set of these Key Performance Indicators (KPIs) defined early in the project lifecycle through consultation with industry stakeholders and consortium experts. Each KPI is measured before and after the deployment of BTs using harmonized templates and field data collection protocols according to each technology analyzed. A control group (baseline) and treatment group (BT-enhanced) have been established for each use case. Field data has been analyzed quantitatively and qualitatively, with statistical validation methods ensuring reliability and comparability.

The impact assessment framework has employed over 40 KPIs across four dimensions, identifying the most relevant in the next paragraphs:

A. Economic

As Lifecycle Cost Analysis, material and energy use. Economic indicators assess the lifecycle cost and resource efficiency associated with BT deployment:

- Lifecycle Cost (LCC): Total cost over the operational lifespan of the solution, including acquisition, operation, and maintenance.
- Labor efficiency: Cost and time saved per worker per task due to automation or support systems.
- Material utilization: Reduction in material consumption per unit of output.
- Energy consumption: Energy savings attributable to optimized processes and autonomous operations.

These KPIs are essential for cost-benefit analyses and align with EU sustainability and competitiveness goals [30].

B. Environmental

Environmental KPIs measure the ecological impact of the BTs and their contributions to decarbonization and circular economy goals:

- Global Warming Potential (GWP): CO_2 equivalent emissions per task or per m^2 of built infrastructure.
- Water use and waste: Amount of water and waste materials generated.
- Noise and pollution: Site-level reduction in noise and airborne pollutants.
- Biodiversity contribution: Positive environmental functions, e.g., in reef-producing AM structures.

These KPIs follow the LCA methodology and contribute to Green Public Procurement (GPP) compliance [31].

C. Social

Social KPIs address worker well-being, inclusion, and safety:

- Fatigue detection: Frequency and accuracy of fatigue-related alerts from wearables.
- Posture quality: Analysis of ergonomic risk based on wearable sensor data.
- Gender inclusivity: Adaptation of technologies to fit diverse body types and needs.

- Safety perception: Survey-based indicators of perceived safety before and after BT deployment.

These KPIs ensure that technology adoption aligns with ethical, inclusive, and human-centric goals, consistent with Horizon Europe's values [32], [33].

D. Technical

Focused on main concepts such as autonomy, productivity or accuracy of task execution. These KPIs measure the functionality, efficiency, and accuracy of BTs in the construction context. They include:

- Task execution time: Reduction in time required to complete specific operations.
- Automation rate: Percentage of a workflow autonomously executed.
- Failure rate: Number of failures or rework events per operation.
- System uptime: Operational availability of BTs during deployment.

These indicators provide insights into the maturity and robustness of BTs and inform decisions about scaling and replicability

These KPIs were applied consistently across all demonstrations to ensure comparability and traceability of results, collected using pre-defined templates and measurement protocols. The combination of these KPIs allows the project to generate replicable, data-driven evidence for the effectiveness and impact of BEEYONDERS technologies in real-world construction environments [34], [9].

7. Results Overview

The results obtained from the BEEYONDERS project highlighted the transformative potential of integrated digital and automation technologies in the construction sector. This analysis was conducted across the six use cases previously mentioned, each evaluating a subset of the project's BTs in real-world conditions. The comparison between baseline and BT-enhanced workflows, based on the KPI framework previously outlined, provided a comprehensive view of performance gains, social acceptance, and environmental contributions.

A. Technical Performance

The results obtained for each BEEYONDER's technology is explained below, highlighting the most relevant achievements:

Robotics and Autonomous Systems

In tunnel excavation environments, autonomous wheel loader in combination with aerial robotic platforms achieved a 9–11% reduction in cycle time through the integration of real-time terrain mapping and adaptive path planning. Onboard sensor fusion and AI-based obstacle avoidance enabled efficient navigation in confined and unstructured spaces, increasing equipment utilization by 12% and reducing mechanical wear.

Aerial robotic platforms designed for GPS-denied environments achieved 95% autonomous coverage of inspection paths using multimodal SLAM (Simultaneous Localization and Mapping), combining LiDAR (Light Detection and Ranging), radar, stereo vision, and thermal imaging. Redundancy strategies enabled mission continuity despite signal degradation, crucial for tunnel and indoor applications.

Additive Manufacturing (AM) for harsh environments

The project's 3D printing solutions for offshore and coastal infrastructure demonstrated improvement in dimensional accuracy, enabled by parametric control and adaptive nozzle calibration systems. Complex geometries, such as caissons and artificial reef structures, were manufactured with low-carbon and fiber-reinforced mortars engineered for resistance to saline exposure and dynamic loads.

Integrated digital process monitoring systems facilitated closed-loop control of the AM process, reducing failure rates and enhancing print repeatability.

Digital Twin tools

BEEYONDERS developed interoperable digital twin frameworks that allowed real-time synchronization between physical assets and their virtual replicas. Field trials showed that deviation between as-designed and as-built models decreased, thanks to automated comparison tools using LiDAR and photogrammetry data.

AI-based perception and planning systems

The deployment of AI-driven perception modules enabled advanced scene understanding in dynamic and visually degraded environments. Key outcomes included:

- Automated detection and segmentation of construction objects.
- Smart scheduling assistants, that dynamically rescheduled tasks in response to equipment delays or weather disruptions, resulting in overall project time reduction in pilot simulations.

Smart wearables and embedded sensor systems

Smart wearables equipped with GNSS, IMU, and biometric sensors were tested for real-time worker tracking and safety monitoring. Technical validation results included:

- Faster emergency response times via automatic geolocation and fatigue alerts.
- Posture detection algorithms for ergonomic risk assessment.

Finally, exoskeleton prototype, equipped with force and motion sensors, showed a reduction in perceived physical strain during repetitive handling tasks. Data from these systems also fed into AI-based safety dashboards, enabling proactive risk mitigation.

B. Economic Feasibility

The deployment of BEEYONDERS BTs demonstrated strong potential for cost reduction, productivity gains, and improved resource allocation across multiple construction sectors.

Lifecycle Cost Analysis (LCC)

A comprehensive Lifecycle Cost Analysis (LCC) performed across pilot sites showed average reductions in total construction-related expenses. These savings were attributed to several synergistic effects:

- Labour hour reductions driven by automation of repetitive tasks and AI-assisted planning.
- Material waste reduction achieved via real-time quality control in Additive Manufacturing and improved cutting/assembly precision from digital twin-based planning.
- Energy efficiency gains in robotic excavation and printing processes, including lower fuel and electricity consumption due to optimized task sequencing and smart control systems.

Building Construction Use Case

In building construction pilots, the integration of wearable safety systems, smart scheduling tools, and digital site management increased labour efficiency. Key contributors included:

- Fewer workflow interruptions, due to automated alerts and digital coordination across teams.
- Reduction in delays caused by safety incidents or miscommunication.
- Enhanced synchronization between deliveries, tasks, and workforce availability, minimizing downtime.

Digital planning tools reduced rework by identifying design clashes and sequencing issues early, cutting corrective labour and materials.

Additive Manufacturing

In AM-based infrastructure elements, the use of optimized printing paths, precise material dosing, and AI-driven print monitoring enabled:

- Relevant material savings compared to traditional casting methods.
- Shorter production cycles, due to reduced formwork handling and integrated curing monitoring.

The reuse of digital models for multiple components also led to scale economies and accelerated design iteration without new tooling.

Robotics and Autonomous Systems

The adoption of teleoperated and autonomous earth-moving and inspection robotic machinery reduced operational costs in tunnel construction:

- Fuel and maintenance savings due to optimized operation cycles and gentler algorithm-guided trajectories.
- Fewer operator hours required per task, with remote supervision or human-in-the-loop models reducing overall deployment costs.
- Remote and autonomous inspections conducted by drones and robotic platforms demonstrated the availability to replace manual methods in confined or hazardous areas, while simultaneously reducing risk exposure.

Cost of Safety and Insurance

Smart wearable deployment led to measurable cost reductions in safety-related areas:

- When fully implemented, it is expected fewer injury-related work stoppages, with pilot sites reporting a potential decrease in minor incidents and near-misses.
- Insurance premium reductions are also expected in high-risk projects where real-time monitoring and predictive risk dashboards were in place.

C. Environmental Benefits

The introduced environmentally sustainable approaches for construction has been successful by leveraging digitalization, automation, and advanced material strategies, resulting in quantifiable improvements in carbon footprint, resource efficiency, and ecological integration.

Reduction in Greenhouse Gas Emissions

Global Warming Potential (GWP) metrics—assessed using standard LCA methodologies (EN 15804+A2)—showed a reduction in CO_2-equivalent emissions. Key drivers included:

- New maritime caisson design in concrete, specially designed to be printed with AM technologies.
- Optimized 3D concrete printing (3DCP) paths, which minimized idle nozzle time, tool movement, and energy consumption.
- Use of custom low-carbon cementitious mixtures, incorporating supplementary cementitious materials
- On-site fabrication via AM, reduced emissions associated with transportation and heavy lifting logistics.

Moreover, robotic systems with energy-aware planning algorithms in road construction reduced fuel consumption, further contributing to lower emissions.

Efficient Use of Water and Raw Materials

In digitalized AM scenarios, closed-loop material handling systems enabled a reduction in water usage and minimization of waste slurry and material overuse.

Biodiversity Enhancement through Bio-responsive Design

The AM artificial reef structures, fabricated and deployed as part of marine pilot, demonstrated significant potential for enhancing local biodiversity.

Reduction of Construction Site Environmental Footprint

BEEYONDERS autonomous and teleoperated technologies contributed to the mitigation of site-related environmental pollution, such as lower particulate emissions.

Alignment with Circular Economy Principles

BEEYONDERS has promoted material reuse and recyclability by embedding digital traceability within digital twin models to enable future deconstruction planning and selective recycling.

D. Social And Human-Centric Impact

BEEYONDERS placed a strong emphasis on human-centric innovation, ensuring that all BTs were not only technically effective but also socially inclusive, ethically sound, and aligned with the needs of diverse construction workers. The project addressed key dimensions such as safety, ergonomics, gender inclusiveness, aging workforce support, and overall worker well-being.

Enhanced Safety and Health Monitoring

The deployment of wearable safety technologies equipped with GNSS, IMU, and biometric sensors resulted in significantly faster alert response times in pilot environments. Data analytics platforms, integrated with fatigue and posture detection algorithms, enabled:

- Real-time notifications to site supervisors in the event of abnormal biometrics (e.g., heart rate spikes, prolonged physical strain).
- Estimated prevention of multiple minor and near-miss incidents over the course of the project, particularly during high-risk operations on both manual handling operations where a significant effort is usually present, as well among the interaction between autonomous machinery and the presence of workers.
- Early identification of fatigue cycles, prompting task rescheduling or rotation before safety thresholds were breached.

This proactive, data-driven approach contributed to a culture of prevention, complementing traditional personal protective equipment (PPE) strategies.

Inclusivity for Vulnerable Groups

BEEYONDERS technologies were intentionally designed for adaptability and ease of use across different user profiles. Particular consideration was given to:

- Older workers, through the introduction of ergonomically supportive tools (e.g., exoskeletons) and user-friendly human-machine interfaces (HMIs).
- Female workers, who remain underrepresented in the construction sector, were actively engaged in co-design workshops and pilot trials. Their participation was incentivized through inclusive training and task assignments where wearable and robotic technologies reduced exposure to heavy manual tasks and occupational strain.

Worker Satisfaction and Perception of Technology

Pre- and post-deployment surveys conducted at demonstration sites showed a marked increase in overall worker satisfaction, particularly in the following dimensions:

- Physical well-being: It is expected a reduced physical strain, notably in repetitive tasks such as screwing, lifting, and positioning.
- Technology acceptance: scepticism decreased over time, especially among older and lower-skilled workers, as familiarity with the tools grew through hands-on use and training.

It is expected a highlighted improved confidence and task accessibility in female workers, since BTs can serve as an enabler for a more gender-diverse workforce when paired with inclusive site policies.

Ergonomic Innovation

The BEEYONDERS human-centric technologies, integrated into several pilot workflows, demonstrated significant ergonomic value:

- Average reduction in perceived exertion, based on Borg scale self-assessments during tasks involving static postures, overhead work, and repetitive bending.
- Improved mobility and comfort, as reported by users who noted better posture support and reduced muscle fatigue by the end of shifts.
- Minimal interference with task execution, owing to careful anthropometric design and feedback-informed iterations.

Pilot evaluations confirmed that exoskeletons and smart wearables, when combined with task redesign and rotation strategies, contribute to long-term musculoskeletal disorder (MSD) prevention.

Digital Inclusion and Skill Development

A central component of BEEYONDERS was to ensure that digital transformation did not leave workers behind. To this end, it has been released the following aspects:

- Custom training programs were developed using XR-based simulations and interactive manuals in multiple languages, ensuring accessibility for both skilled and low-skilled workers.
- Digital tools were co-developed with user feedback loops to maintain high usability and low learning curve.

These efforts supported not only safe integration of technology but also social sustainability through lifelong learning and equitable access to innovation.

E. Strategic And Ecosystem-Level Outcomes

The successful demonstration of European-developed BTs in international settings, including the Japan-EU use case, validated the project technological improvement in critical domains on a set of different and representative construction scenarios.

Standardization activities and regulatory engagement began shaping frameworks for wearable safety devices, autonomous machinery and interoperable digital twins. Data and feedback collected provided replicable templates for other stakeholders seeking to adopt similar innovations in the construction sector.

Overall, BEEYONDERS demonstrated that digitalization and automation, when grounded in inclusive and sustainable practices, can significantly elevate construction sector productivity, safety, and environmental performance. These results serve as a foundation for further commercial exploitation, policy alignment, and scaling across diverse infrastructure contexts.

8. CONCLUSIONS

The BEEYONDERS project has demonstrated that a coordinated, multi-technology approach can significantly transform the construction sector by embedding breakthrough digital and automation solutions directly into field operations. From autonomous vehicles and advanced wearables to AM and integrated digital twin platforms, the project has addressed both longstanding and emerging challenges in the industry—labor shortages, sustainability imperatives, safety, and technological dependency.

A key strength of BEEYONDERS lies in its systems-level integration: rather than focusing on isolated innovations, it delivers a holistic framework in which smart tools communicate, adapt, and respond to human needs and environmental constraints. This has been critical for proving not just technical feasibility but real-world impact across economic, social, and ecological metrics.

The project's results illustrate that:

- Productivity can be measurably increased through autonomous and collaborative robotics.

- Worker safety and inclusivity can be enhanced with human-centric technologies such as smart PPE and adaptable exoskeletons.
- Environmental impacts can be mitigated through AI-optimized lifecycle-informed design.
- Decision-making can be transformed through real-time, data-rich digital twins.

Looking forward, several directions are proposed:

- Scaling and industrial adoption: Wider uptake by SMEs and construction operators is essential. BEEYONDERS provides validated tools, training modules, and standardization pathways to support this.
- Policy and regulation alignment: Continued engagement with standardization bodies and regulatory stakeholders will ensure that BTs can be safely and efficiently introduced into mainstream construction.
- Continued R&D investment: Emerging fields such as cognitive robotics, adaptive digital twins, and bio-integrated materials merit further exploration.
- International cooperation: The EU–Japan collaboration exemplifies the value of global alignment. Future projects should continue this model of cross-border technology exchange.

In conclusion, BEEYONDERS offers a forward-looking blueprint for how the integration of disruptive technologies can lead in the construction of the future—smart, safe, sustainable, and optimized.

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REFERENCES

- European Construction Sector Observatory. (2021). Digitalisation in the construction sector: Analytical Report. European Commission.
- European Commission – EU Funding & Tenders Portal. Topic details. Horizon CL4 2021 Twin Transition 01-12.
- BEEYONDERS website. Retrieved from https://beeyonders.eu
- Leonard, "In Japan, robotics and construction work side-by-side," Leonard by Vinci, 2020. [Online]. Available: https://leonard.vinci.com/en/in-japan-robotics-and-construction-work-side-by-side/
- Japan Inside, "Japan experimenting with robotic bulldozers & drones in construction – Aren't enough workers," JapanInside.com, 2019. [Online]. Available: https://japaninsides.com/japan-experimenting-robotic-bulldozers-drones-construction-arent-enough-workers/
- Eurostat, "Ageing Europe – Looking at the lives of older people in the EU," European Union, 2023. [Online]. Available: https://ec.europa.eu/eurostat/web/products-statistical-books/-/ks-02-20-655
- European Commission, "The European Green Deal and Fit for 55 package," European Commission - Climate Action, 2021. [Online]. Available: https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal_en
- Lyon et al. (2025) – Human-Centered Design to Enhance Implementation and Impact in Health. Annual Review of Public Health, Vol 46, 467–485.
- BEEYONDERS Consortium. (2024). Common Methodology and Specifications for Case Study Development and Technology Integration Assessment (D7.1). Horizon Europe Project Deliverable.
- BEEYONDERS Consortium, System Requirements (D2.1), Horizon Europe Deliverable, Nov. 2022.[11] Dadhich, S., Bodin, U., & Andersson, U. (2016). Key challenges in automation of earth-moving machines. Automation in Construction, 68, 212–222.
- H. Hu, J. Wu, S. Wang, Y. Lin and K. Lv, "Voronoi-based multi-robot autonomous exploration in unknown environments via deep reinforcement learning," IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 14413–14423, Dec. 2020.
- Nocerino, F. Menna, F. Remondino, and M. Toschi, "Aerial photogrammetry and inspection in construction: State of the art," ISPRS Archives, vol. 42, pp. 417–424, 2018.
- Bos, R. Wolfs, Z. Ahmed, and T. Salet, "Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing," Virtual and Physical Prototyping, vol. 11, no. 3, pp. 209–225, 2016.
- S.-M. Mäkelä et al., "Activity recognition of construction workers using inertial motion units," Zenodo, 2022. [Online]. Available: https://doi.org/10.5281/zenodo.5828316
- Mäkelä, S.-M., Lämsä, A., Keränen, J., Liikka, J., Ronkainen, J., Peltola, J., Häikiö, J., & Bordallo, López M. (2022). VTT-ConIoT: A realistic dataset for activity recognition of construction workers using inertial motion units. Zenodo. https://doi.org/10.5281/zenodo.5828316
- Zhu, Z., Dutta, A., & Dai, F.J.A.i.C. (2021). Exoskeletons for manual material handling – A review and implication for construction applications. Automation in Construction, 122.
- M. de Looze, T. Bosch, F. Krause, K. Stadler, and L. O'Sullivan, "Exoskeletons for industrial application and their potential effects on physical work load," Ergonomics, vol. 59, no. 5, pp. 671–681, 2016.

- J. L. Herberts, R. de Groot, and D. D. Groen, "Development of a back-assist exoskeleton for construction work," Construction Innovation, vol. 20, no. 2, pp. 203–222, 2020.
- Botín-Sanabria, D. M., Mihaita, A. S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. D. J. (2022). Digital twin technology challenges and applications: A comprehensive review. Remote Sensing, 14(6), 1335. https://doi.org/10.3390/rs14061335
- Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. Computers in Industry, 130, 103469.
- https://doi.org/10.1016/j.compind.2021.103469
- Mersky, A. C., & Samaras, C. (2021). Fuel economy benefits of autonomous vehicles: Review and reanalysis. Transportation Research Part D: Transport and Environment, 92, 102716.
- https://doi.org/10.1016/j.trd.2020.102716
- Wadud, Z., MacKenzie, D., & Leiby, P. (2020). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A: Policy and Practice, 136, 1-18.
- https://doi.org/10.1016/j.tra.2020.03.024
- ACCIONA. (2021, 8 de octubre). Kugira, el coloso artesano. Experience ACCIONA. https://experience.acciona.com/es/kugira-coloso-artesano/
- La Vanguardia. (2017, 20 de noviembre). Así es el Kugira, la 'ballena' tecnológica que amplía el Puerto de Barcelona. https://www.lavanguardia.com/economia/20171120/433022365044/kugira-dique-flotante-acciona-amplia-puerto-de-barcelona.html
- Serrano-González, J., & Álvarez-Izquierdo, P. (2020). Lean construction and rework reduction: A case study in European building projects. Construction Management and Economics, 38(7), 625-641.
- Koskela, L., & Vrijhoef, R. (2021). The impact of poor planning on construction rework: Evidence from European residential projects. Journal of Engineering, Design and Technology, 19(4), 892-908
- Burghardt, T. E., & Pashkevich, A. (2021). Durability and maintenance challenges of road markings in European climates. Road Materials and Pavement Design, 22(5), 1123-1139.
- Carlson, P. J., & Picha, D. L. (2019). Retroreflectivity degradation of road signs and pavement markings: A European perspective. Transportation Research Procedia, 42, 123-135.
- Sanz, A., & Gómez, P. (2022). Vegetation encroachment and its impact on road safety and maintenance in Southern European highways. European Transport Research Review, 14(1), 18.
- United Nations, Transforming our world: The 2030 Agenda for Sustainable Development, United Nations, 2015. [Online]. Available: https://sdgs.un.org/2030agenda
- European Commission, Buying Green! A Handbook on Green Public Procurement, 3rd ed. Luxembourg: Publications Office of the European Union, 2021. [Online]. Available:

https://op.europa.eu/en/publication-detail/-/publication/4a407ec0-8278-11eb-9ac9-01aa75ed71a1

- European Commission, Orientations towards the first Strategic Plan for Horizon Europe: Implementation of the Strategic Planning Process, Luxembourg: Publications Office of the European Union, 2020. [Online]. Available: https://ec.europa.eu/info/publications/orientations-towards-first-strategic-plan-horizon-europe_en[33]
- BEEYONDERS Consortium, Workers KPIs (D2.4), Horizon Europe Deliverable,2023.
- BEEYONDERS Consortium, Testing Plan and Report (D2.5), Horizon Europe Deliverable, 2024.