REPORT ON LIVING LABS AND TASK ASSESSMENT

Deliverable D5.3

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SHORT ABSTRACT	This deliverable contains a comprehensive report on the living lab and corresponding activities on the construction testbed in the framework of TARGET-X.
KEY WORDS	Construction, Living lab, testbed, 5G, Robotic Deconstruction,
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Executive Summary

Whilst the term '5G' has become a commonplace mention in discourse pertaining to public networks for private end-user communication, it has yet to be adopted by a significant number of verticals. This constitutes the point of departure for the TARGET-X project. In a collaborative initiative, researchers from diverse disciplinary backgrounds are working in synergy to explore novel use cases and applications. This deliverable reports and documents the outcomes of the living lab in construction established at the Reference Construction Site in Aachen, where several developments across verticals have been deployed and validated.

The report highlights the potential of 5G to transform safety and sustainability in onsite processes, with a particular focus on a controlled deconstruction use case. The objective is to explore the ways in which 5G can contribute to the development of safer, more sustainable, and more circular economic practices in the construction vertical. The deployed approach consists of an automated robotic deconstruction system, capable of unbolting standardized steel connections using AI-based perception, force–torque sensing, and custom end effectors. Second, extended reality (XR) technologies were integrated to support operator-in-the-loop planning and supervision, enabling collision checks, reachability tests, and alignment of virtual and real environments. Third, a safety assistant system was deployed, combining LiDAR-based environmental monitoring with AI detection to ensure safe human–robot collaboration on site.

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List of Acronyms and Abbreviations

5G-ICE	5G-Industry Campus Europe
AI	Artificial Intelligence
AR	Augmented Reality
CCR	Construction Robotics GmbH
CPE	Customer Premises Equipment
CUDA	Compute Unified Device Architecture
GPU	Graphics Processing Unit
HMD	Head-mounted XR device
IFC	Issued for Construction
IoT	Internet of Things
IP address	Internet protocol address
KPI	Key performance indicators
KVI	Key value indicator
LBD	Linked Building Data
LiDAR	Light Detection And Ranging
MAF	Methodological Assessment Framework
mmW	Millimetre Wave
NTP	Network Time Protocol
QAM	Quadrature amplitude modulation
RAM	Random access memory
ROS	Robot Operating System
RWTH-ACS	Institute for Automation of Complex Power Systems, RWTH Aachen University
RWTH-IP	Chair of Individualized Production, RWTH Aachen University
SPARQL	SPARQL Protocol And RDF Query Language

TDD	Time Division Duplex
UI	User Interface
XR	Extended Reality
YOLO	You Only Look Once (computer vision model that is used for object detection)

1 Introduction

This deliverable presents the outcomes of the robotic deconstruction activities carried out at the living lab Reference Construction Site on Campus Melaten in Aachen. The task focused on demonstrating automated deconstruction processes using advanced robotic machinery under real construction site conditions. The testbed served as a relevant, close-to-operational environment for integrating and evaluating network technologies, as well as the hardware and software components required for the envisioned use cases.

Within this context, the project investigated several critical aspects of automated deconstruction. These included the controlled deconstruction of a steel element, the potential to increase the share of reusable materials, and the establishment of a closed digital loop linking digitalized construction with controlled deconstruction processes. The role of emerging 5G/6G functionalities in enabling such capabilities was a central focus of the evaluation.

1.1 Relations to other activities

The activities in work package 5 “Construction” overlap with work package 3 “Energy”, work package 1 “Methodological Assessment Framework” (MAF) and work package 6 “Technology Evolution”.

The collaboration with work package 3 has output the Meter-X device. It is a power metering device, which was developed at the RWTH-ACS department and integrated on the construction testbed. It is used to measure and analyse the electrical power consumption of different construction machinery under varying loads. A joint paper was presented at the 2025 European Conference on Computing in Construction conference [1]. Apart from that, there is an overlap with the activities in work package 1, “Methodological assessment framework”. The use cases prototyped in work package 5 and their specifications provided input to the development of the methodological assessment framework [2, 3].

Furthermore, MAF assessed the efficiency gains achievable through automation, while also considering the benefits of live on-site information for enhancing worker safety. By comparing the outcomes of robotic deconstruction against conventional procedures, this deliverable provides insights into both the technical advancements and the practical challenges associated with implementing automated methods in dynamic and robust construction environments. The results will be reported in deliverable D9.5.

In collaboration with Qualcomm in the context of work package 6 “technology evolution” activities, a mmWave setup was installed temporarily on the construction testbed to investigate the potential benefits of features such as increased uplink for future construction and robotics use cases.

1.2 Document overview

This document contains the report on the living lab activities of the prototype deconstruction system as part of TARGET-X work package 5. Building upon the overall description of the 5G Construction Testbed and its function of serving as a collaborative platform for all FSTP partners and the core consortium (see section 2), section 3 provides a report on construction use cases and task assessment. Each subsection will highlight the main activities regarding the sub-development parts of the overall deconstruction process (see 3.1 – Development of an automated deconstruction machinery; 3.2 - XR technology for robotic-aided deconstruction planning and 3.3 – Safety assistant system for (de)-construction robots). The report concludes with a summary of the living lab activities (see Section 4).

2 The TARGET-X construction testbed

Throughout the 34 months project duration of TARGET-X, the construction testbed has been converted into a living lab and trial platform for the application of 5G technology to construction use cases. While the research activities of the consortium members within the work package 5 “Construction” focused on leveraging 5G for a controlled deconstruction scenario, the beneficiaries of two rounds of Open Calls explored the potential of 5G to address their very individual, mostly highly company-specific challenges.

2.1 Setting up the infrastructures for a living lab

Before the construction vertical’s use cases and the mentoring of a total of 17 FSTP projects could be rolled out, the construction testbed needed to be prepared in terms of communication and compute infrastructure. The starting point was the facilities of the “Reference Construction Site” operated by the Construction Robotics GmbH (CCR) that had moved to the RWTH Aachen Campus Melaten. By this relocation of the testbed, an integration of the previously strictly construction related testbed into the network infrastructure of the 5G Industry Campus Europe (5G-ICE) [4] was made possible. The dedicated outdoor cell has been up and running since the summer of 2023. To get access to the network, dedicated SIM cards are required. The configuration and distribution were organized by Fraunhofer IPT, who also coordinate the operation of and activities related to the 5G-ICE network. A first set of these SIM cards has been handed out to CCR with the commissioning of the construction testbed network cell. Each construction machine and other 5G capable equipment involved in the TARGET-X construction use cases were assigned their own SIM card. A second set of SIM cards was configured after twelve projects had qualified for mentoring in the second Open Call and were expected to need SIM cards when conducting their tests and trials at the construction testbed. The IP-addresses of the SIM cards are configured such that they are discoverable from within the 5G-ICE network cell on the construction testbed and additionally within the internal RWTH Aachen University network. While by this choice access from the 5G network on the construction testbed to “the internet” is granted, the IP-addresses cannot be discovered from outside either of these networks.

Physically, the network was based on the product *Ericsson Private Networks*. In the initial deployment, the radio unit of type “Ericsson 4408” as well as an omni-antenna of type *AW3374-T0-F* from Alpha Wireless were mounted on a small, bottom-slewing tower crane at location 1 on the testbed layout shown in Figure 1. In the course of the project, it was moved to location 2, in combination with a directional antenna of type *Ericsson integrated directional antenna 6524* mounted on the tower of a top-slewing tower crane that was brought to the testbed by one of the beneficiaries of the second Open Call. This new mounting has the advantage of overcoming the need for complex wiring solutions for the optical fibre cables.

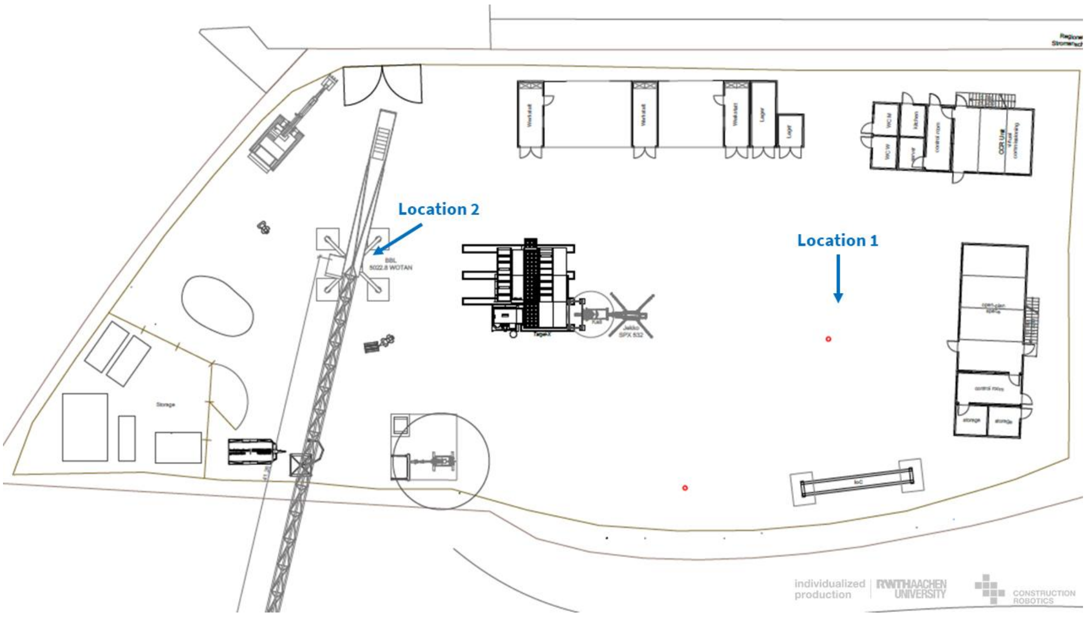

Figure 1:Site plan of the Reference Construction Site with both antenna locations marked

Taking a closer look at the network architecture and the distribution of computational capacities as shown in Figure 2, the nested structure becomes evident.

Figure 2: Overview 5G Reference Construction Site with TARGET-X components

As none of the construction machines had a 5G-network interface at the beginning of the project, they were equipped with 5G-capable telecommunication hardware that was then connected to the internal compute and or control units of the machines. Thus, the machines became host platforms for network devices. As a consequence, they were theoretically able to communicate with each other via the 5G network but also to other equipment with an IP-address from the specified pool. However, for the practical implementation in the use cases, port mapping and forwarding was necessary on the network devices onboard of the machines. Otherwise, operations like publishing messages over MQTT would have failed due to undiscoverable brokers and further reasons. To time synchronize the construction machines and other use-case-related user equipment on the construction testbed, the *Chrony*[1] service for Network Time Protocol (NTP) was installed on the local computing hardware of the machines. It was then used to synchronize the system clocks of the local computers with an NTP timeserver provided by the RWTH Aachen University available under the IP-address:

134.130.5.17; ntp2.rwth-aachen.de; location: Seffenter Weg [5]

Another key element of the network and compute architecture on the construction testbed is an edge server located inside one of the construction site containers on the testbed. It is accessible from within the 5G network as well as the internal RWTH Aachen University network. The hardware was built on the basis of a DELL Poweredge R760 platform that holds two 20C/40T Intel Xeon processors, four Nvidia A40 GPUs and 512GB of RAM. On the software level, several containerized services operate on the Debian operating system of the edge server and act as the backbone for most of the use cases onsite. Furthermore, for consistency, the edge server is time-synchronized to the same NTP timeserver as the construction machines.

2.2 Creating a platform for collaboration within TARGET-X

Though the preparations of the construction testbed in terms of physical and digital infrastructure had been completed and reported with milestone 5.1 at the end of 2023, the start of the first round of FSTP projects at the beginning of 2024 created a new demand for the testbed. The beneficiaries of the first Open call, all representing different trades or stakeholders of a typical construction project, had applied with a highly diverse range of projects. To streamline the projects and corresponding activities on the testbed, mentors and beneficiaries agreed on creating a joint demonstrator building on the testbed into which they could integrate their individual projects and research and development activities. Moreover, this demonstrator should be extendable to provide a platform for future research, e.g., the second generation of FSTP projects. With this decision, the “ReStage multi-material demonstrator” was born (see Figure 3).

[1] https://chrony-project.org/

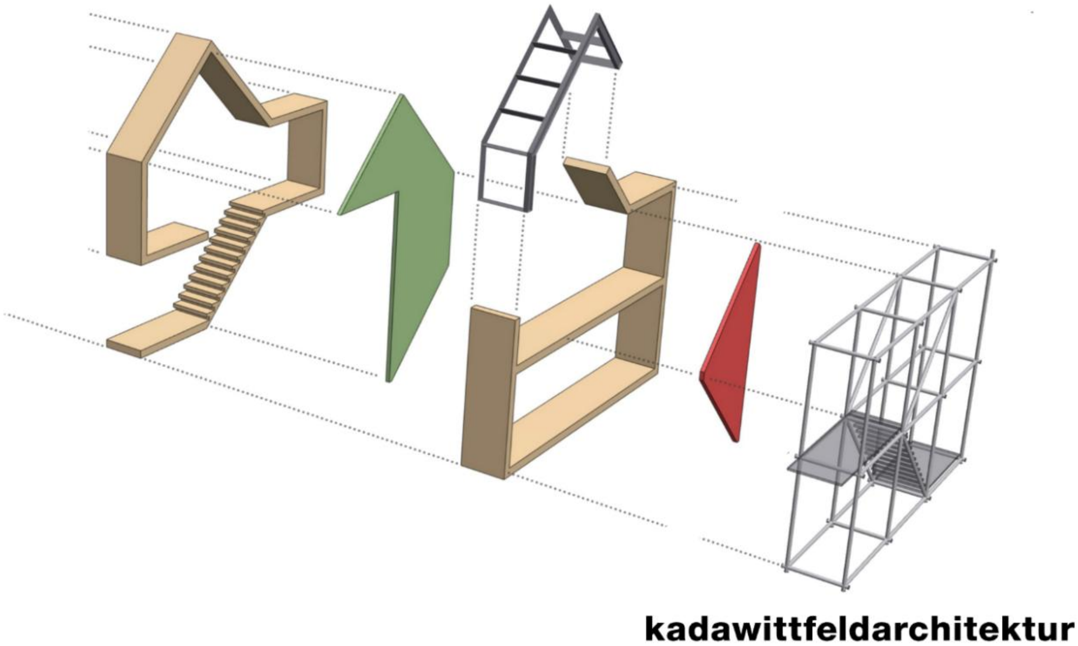

Figure 3: First sketch of the multi-material collaborative ReStage Demonstrator

In contrast to a real-world construction project with a very linear value chain, for the design and planning of “ReStage” all stakeholders represented by the Open Call beneficiaries participated from the very beginning. Only a single design constraint was stated by the mentors from CCR and RWTH-IP: Each joint or connection between building elements and construction materials should be detachable, for example, bolted connections between steel elements instead of weld connections. Despite the unconventional setting, all stakeholders joined the experiment, and after a team effort the roofing ceremony took place on 8th August 2024 (see the left picture in Figure 4). The right picture Figure 4 shows the final state of the “ReStage” structure after the first open Call.

Figure 4: Left: Roofing ceremony, Right: Final state of “ReStage” after first open call

Now that a shell structure existed on the test bed, offering ideal conditions for an extension, many of the beneficiaries from the second round of open calls intended to interact with the demonstrator within their projects. Some added new elements or even entire modules to the building, while others used data from the initial planning or construction phase. In total 17 projects and 27 entities contributed to the creation and subsequent use of "ReStage". Figure 5 shows on the left side the front view of the demonstrator after the second open call, with an additional steel/timber unit. The right side highlights another project focusing on 5G for monitoring façade greening systems.

Figure 5: Final ReStage demonstrator on Reference Construction Site in Aachen after the second Open Call (front & back)

Aside from providing a collaborative platform and a realistic construction demonstrator with multiple materials and stakeholders for evaluating 5G technology, the "ReStage" structure also serves as the foundation for the deconstruction use case of TARGET-X work package 5. Details of the development, execution, and on-site validation will be described in the next section 3.

In addition, the testbed serves also as a platform for the collaboration within the core consortium and the other work packages. The Meter-X device from WP3 could be tested on a construction machine for use in analysing power consumption as published in [3]. The deconstruction set up and process underwent rigorous evaluation in the scope of the Methodological Assessment Framework from WP1, which serves as a tool to evaluate the 5G-related key performance indicators (KPIs) and key value indicators (KVIs).

3 Report on construction use cases and task assessment

In order to evaluate and assess the deconstruction process carried out in the overall context of the living lab on the construction testbed Reference Construction Site, it is important to consider the individual use cases that contribute to this process as building blocks. Conceptually, the use cases were aligned with the tasks described in the project proposal in work package 5. This chapter explains how the individual use cases were designed and how the individual technical elements were solved in order to be able to carry out the 5G-supported and robotically assisted controlled deconstruction process on the construction testbed. Figure 6 provides an overview of all components and the setup. The Jekko SPX532 orange spider crane was added to the image to illustrate the continuation of the process sequence with the building element to be extracted once unfastened by the deconstruction machinery. The integration of the communication and control of this crane with 5G will be future research.

Figure 6: Deconstruction set up on Reference Construction Site in Aachen

3.1 Development of an automated deconstruction machinery

The TARGET-X demonstrator was designed with standardized HEB120 beams, identical end plates with four bolt holes, and uniform fastening bolts. In addition, the use of self-threading bolts eliminates the need for counter-bolting and facilitates straightforward reassembly. This high level of uniformity made bolted joints particularly well-suited for automation, as the system could be developed for a single connection type and then seamlessly scaled to the entire structure. At the same time, it ensures that both steel members and bolts can be recovered intact and reused, directly contributing to circular construction objectives.

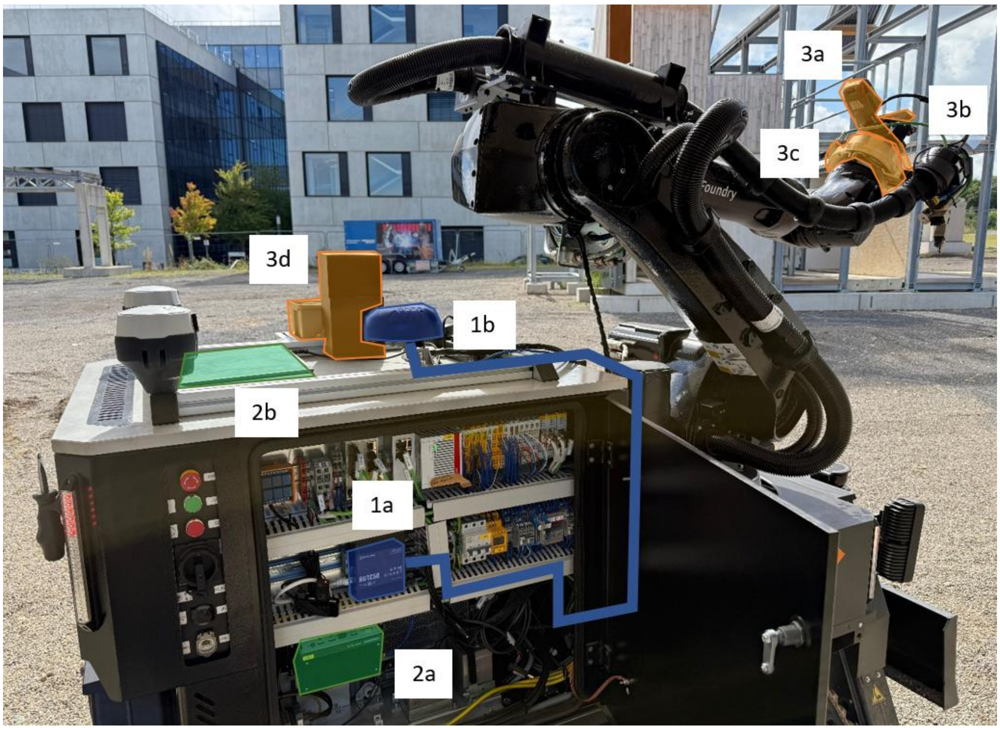

Figure 7: Robotic system setup for deconstruction use case; 1) network integration (blue): 1a) 5G Router Teltonika RUTC50, 1b) External outdoor antenna; 2) computation integration (green): 2a) Integrated low-level control PC, 2b) On-board high-level control PC; 3) process specific device integration (orange): 3a) Impact driver Ingersoll W5300, 3b) Depth camera ZED2i, 3c) Force/Torque sensor (Schunk FTE-Omega-160-IP659), 3d) unfastened bolt gripper (Schunk PGN-plus-E 45)

The system is built around a robotic arm manipulator (KUKA Iontec KR70 R2100) mounted on a caterpillar platform (see Figure 7). This platform is equipped with an on-board PC, hosting low-level control of the manipulator and gathering of sensor data, connected to the 5G network with a dedicated on-board router (Teltonika RUTC50) and an external antenna. Environmental perception is handled by a stereo depth camera (ZED 2i) integrated into the end effector and connected to an onboard PC running dedicated service scripts. The first skill, “bolt-finder”, performs perception tasks, identifying either hexagonal bolts directly or, when bolts are not clearly visible, interpreting the structural relationship between vertical and horizontal beams. For this, AI models (Grounding DINO and SAM2) [4] [5] segment a 2D image into either hexagonal bolt, or vertical and horizontal beam masks, which are then projected onto the stereo vision point cloud to derive accurate spatial information by planar segmentation of surfaces and exporting dominant orientation in space. A second skill, “meta-controller” translates these detections into robot motions, using feedback from the force–torque sensor (Schunk FTE-Omega-160-IP65) to ensure reliable in-process sensor feedback.

When bolts are clearly visible, the robot positions the end effector at the bolt approach position, verifies alignment via tactile sensing, and unbolts the joint using the impact driver (Ingersoll W5300) with live tactile feedback. Under challenging conditions -such as strong reflections, shadows, or weather-dependent lighting- the system switches to an adaptive probing routine for the identification of bolt approach position: the force–torque sensor is used to touch three inner sides of the beam, allowing the robot to infer bolt positions relative to the standardized beam geometry of the structure. Once removed, bolts are captured by a magnetic socket insert and transferred by a parallel gripper (Schunk PGN-plus-E 45) into a storage container at the rear of the platform, ensuring systematic collection. Figure 8 presents the overall unbolting sequence.

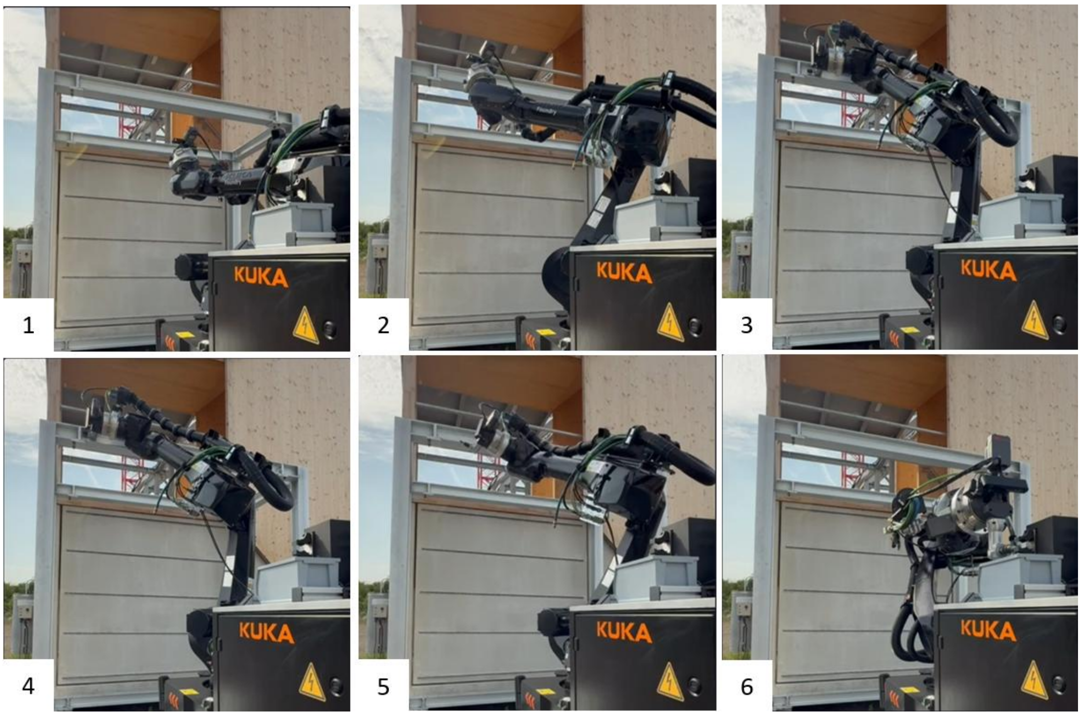

Figure 8: Sequence of unbolting process, 1) starting home position, 2) Inspection position for bolt-finder, 3) beam-approach position, 4) sensing of the bolt and unbolting, 5) retraction with the unbolted bolt, 6) storage in the container

The execution of robot motions and the processing of sensor data are primarily handled on the on-board PC on the robot. The robot control unit is responsible for carrying out single or sequenced motion commands that are in the format of linear or axis motions, through implementation of KUKA|crc [6], while the “meta-controller” interprets feedback from attached sensors and “bolt-finder” script and orchestrates the robot’s actions accordingly. In the current setup, both raw sensor data gathering and robot control are carried out locally on the onboard PC, where the communication between process assets and services is done through the MQTT Broker over 5G connection

The operator interface for this process was developed as a fully web-based application, meaning the UI can be accessed from any 5G-enabled device with a standard web browser. In practice, this allows operators to monitor and interact with the system through portable devices. For this demonstrator, a tablet was used to preview and if needed intervene with the unbolting process in real time.

The development of this UI (see Figure 9) was based on two main components: the *bolt-finder* routine and the *meta-controller* routine. The bolt-finder, written in Python, processes sensor data with AI models and provides a visualization interface built with THREE.js. Through this interface, the robot is shown in a 3D environment with live updates of its joint states, alongside the stereo camera's point cloud data. The outputs of the perception models, including the detected bolts and their position and orientation, are overlaid on the point cloud to give the operator a clear view of the structural elements. The meta-controller, on the other hand, is designed to run through simple MQTT commands. Each step in the unbolting process is published as a state ID on the network, making the routine easy to track and control. Both routines are combined into a single supervisory user interface, implemented with Node-RED and running on the Reference Construction Site's edge server. Through this web-based dashboard, the operator can monitor sensor states, supervise the robot's actions, and take control when needed. Figure 9 shows how this interface is set up.

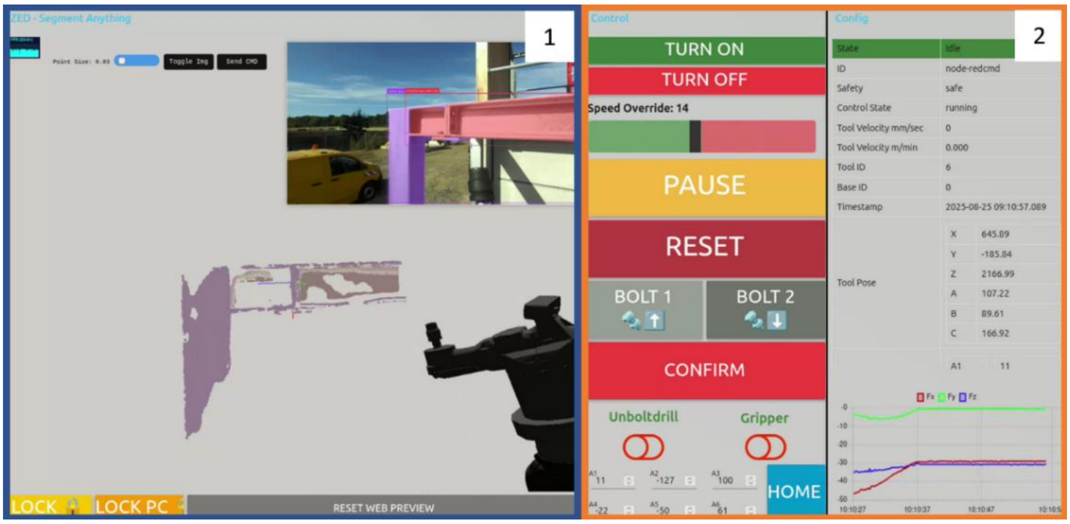

Figure 9: User interface for the monitoring of unbolting process, 1) bolt-finder UI, presents the interactable 3D environment with point cloud and robot as well as the segmented image. 2) meta-controller UI, presents the process commands buttons and live robot state and force/torque feedback.

As for the next step of structural steel beam handling, development of an additional end effector that consists of 24V magnetic grippers has been investigated, which uses the same software architecture described previously for the unbolting process. Figure 10 shows the final prototype of both end effectors.

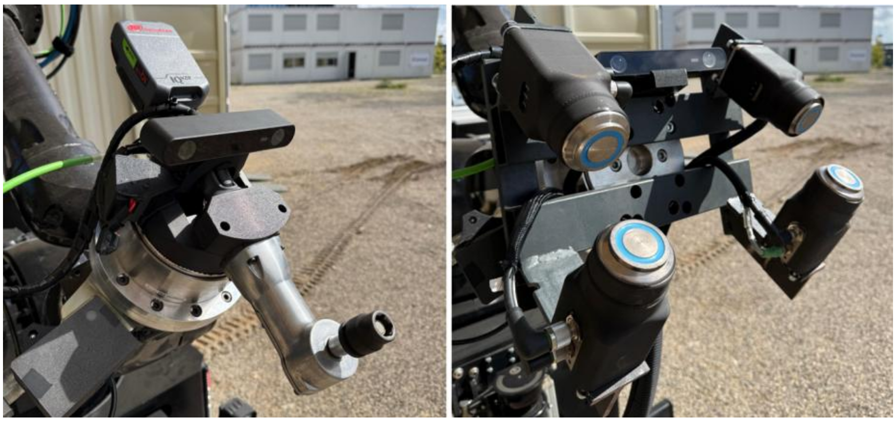

Figure 10: Final prototype of end effectors left the unbolting end effector, right the gripping end effector.

3.2 XR technology for robotic-aided deconstruction planning

Since greater tolerances and deviations between the planned and actual states occur in construction than in manufacturing plants, it is essential to develop methods that make the automated construction process resilient to such deviations. To address this challenge, within the TARGET-X construction use cases, an XR-based approach was chosen that enables the human remote operator of the automated, robot-assisted process to oversee the entire process in real scale via a virtual simulation before approving and initiating it.

In order to check the preplanned robotic path and simulated robotic process in this scenario, it is essential to register the simulation's space in the virtual 3D environment to the actual workspace in the real world on site. Deliverable D5.2 [4] described an approach for registering virtual construction site models to the real, physical construction site based on fiducial markers. In practical application in trials on the construction testbed, this method proved to be highly dependent on lighting conditions and the material of the marker. On the one hand, some markers themselves reflected very strongly when exposed to bright sunlight. Besides that, there were various building materials whose surface reflected strongly, making it almost impossible to distinguish between the background and the markers. In addition, the limited field of view of the integrated camera of the user equipment meant that a relatively large number of markers had to be attached to the ReStage demonstrator in order to maintain stable registration between the virtual and real world throughout the entire workspace and over the entire duration of the process. Not only that, once the marker is outside of the camera view, the application is unable to register itself as it has no information on the current coordinate.

Based on these findings, subsequent project phases investigated approaches that could overcome these limitations while still leveraging human capabilities for object registration in both virtual and real environments. One promising candidate for this approach is Meta Quest 3.

Meta Quest 3 is a head-mounted XR device (HMD) that provides a Mixed Reality (MR) experience by merging both virtual and physical worlds through passthrough technology. This technology captures real-world environments in colour and reconstructs them inside the headset, allowing users to see their physical surroundings while maintaining depth perception. Although primarily used for gaming and immersive experiences, this technology can be adapted for other industries as demonstrated in this deliverable.

To address the previously mentioned shortcomings, we utilize spatial anchor functionality. A spatial anchor serves as a world-locked frame of reference that gives position and orientation to virtual objects by anchoring them relative to real-world locations. This functionality allows users to create multiple spawn points within an environment for different elements, eliminating reliance on fiducial markers entirely. In our use case, two unique spatial anchors are employed: one for building elements and another for machinery (i.e., Kuka robotic arm with a mobile platform).

During the initial phase of deconstruction, users can employ HMDs to visualize elements designated for deconstruction. Information derived from IFC models is queried as linked building data triples from an edge server and parsed by HMDs into meshes with metadata (as shown in Figure 11). The meshes are generated using an architecture described in Deliverable 5.2 (Section 4.1) [4]. With this information at hand, operators can set spatial anchors for robots accurately scaled against physical world references. Using two spatial anchors, one with reference to the actual position of the physical building structure and one with reference to the actual position of the deployed physical robot. They can plan robot reachability concerning relevant building elements efficiently without deploying actual machines first (illustrated in Figure 12), ultimately saving costs through better-informed planning systems.

Figure 11: Highlighting a beam and click to show its properties.

Figure 12: Reachability test using the HMD before deploying the machine.

Once the machine is confirmed to be able to reach the element, the machine is deployed on-site. The coordinates of the entities now share a virtual coordinate and are referenced to each other. Figure 13 shows the position of the spatial anchors that are placed by the operator within the virtual environment using the HMD. The bottom left shows the spatial anchor of the building structure, while the top right shows the anchor point of the robot.

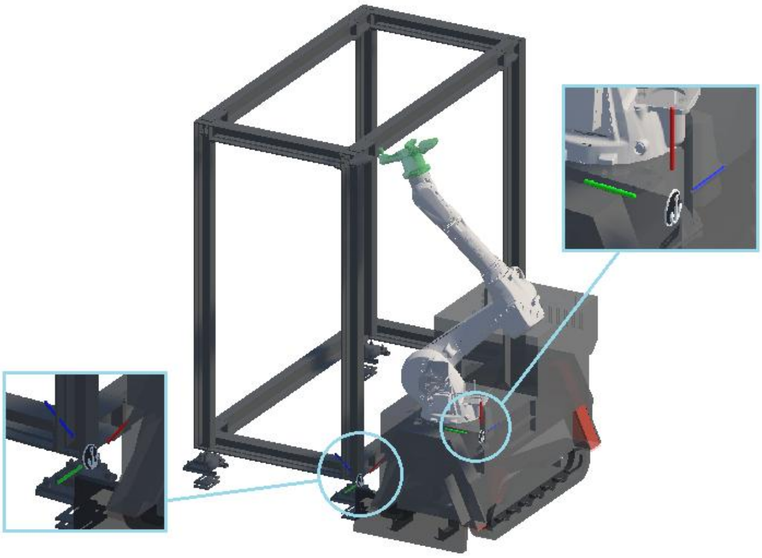

Figure 13: Referenced system of two different elements in the same virtual environment.

Figure 14 illustrates end positions achieved during simulations using HMDs while interacting with steel beams. In this process, operators can visualize potential collisions with nearby elements here too. The top left panel displays live feeds featuring segmentation algorithms from cameras mounted on end effectors discussed in detail in Section 3.1. The panel below shows live force torque sensor information transmitted via the MQTT protocol from brokers hosted on edge servers. After confirming that the paths avoid collisions with the surrounding structures through the visualisations provided by the HMDs' interactions, the above-mentioned steps lead to sending the commands to the message broker on edge server. From the broker on the edge server, subscribed robots receive instructions moving arms accordingly into desired positions. As the arm is moved to the desired rough position and the camera detects the beams and screws, the unbolting sequence is carried out autonomously as described in Section 3.1

Figure 14: Simulation and control of the robot via XR.

This workflow positions both, the structure's and the robot's, physical coordinates into the same virtual environment, thereby registering them into the shared reference coordinate system. This enables operators to visualize, plan, and manoeuvre robots without needing extensive prior technical knowledge around critical aspects such as inverse kinematics or coordinate orientation thereby lowering entry barriers to complicated machinery on-site effectively.

To maximize the framework's flexibility, we deploy another spatial anchor by referencing the entire construction's layout with the HMD. A spatial anchor is placed with reference to the actual layout of the construction site, allowing the user to point and send these coordinates to other robots on the testbed. The aligned layout of the construction site within the HMD allows other robots to drive to the appointed location.

There are, however, some drawbacks to this approach. The Meta Quest 3 does not support 5G natively currently. During the period of this project, there is no standalone 5G solution for HMD natively. In this use case, the HMD is connected wirelessly to an industrial 5G modem. During the execution and testing phase, it was also noticed that it is not possible to wear a safety helmet when using such an HMD, raising concerns about adherence to safety protocols.

3.3 Safety assistant system for (de-)construction robots

The safety of human workers in shared workspaces between humans and semi-automated, fully automated, or even autonomous systems poses a major challenge for the organisation of work processes and task planning. In addition to generally applicable occupational health and safety measures and regulations, further steps are necessary to address the issue of human-machine interaction.

3.3.1 General occupational safety measures on the construction testbed

On construction site, unlike production facilities, where the workspace is separated from the human workspace by structural safety measures such as safety cages or other safety devices, light barriers, and permanent installations are unsuitable for construction site operations. It is also relatively difficult to implement a temporal separation of human and robot activities on construction sites. A detailed discussion of this topic was described by the authors in [5]. Nevertheless, some basic safety measures also apply to construction sites, which are also applied on the Construction Testbed:

- Only authorised personnel have access to the site
- No one is allowed to work alone on the site
- Everyone must wear their personal safety equipment (helmet, safety shoes, high-visibility vest)
- Machines and tools may only be used after prior instruction or training
- When using machines, the safety distances and/or restricted areas defined by the manufacturer must be adhered to

In addition, further restrictions have been imposed on the use of semi-automated or fully automated systems. For example, the maximum speed of autonomous machines has been limited to a slow walking speed. Moreover, the safety areas around the machines specified by the manufacturer have been transferred to the digital modelling of the workspaces and, in most cases, even enlarged.

3.3.2 Special safety measures in the context of the controlled, semi-automated deconstruction process

As the goal of the application of 5G for an automated, controlled deconstruction process is to allow human construction workers to work from a safe distance without the need to enter immediate or potential danger zones onsite, it is necessary to replicate the workspace awareness that a human operator would have by other means. For this purpose, the stationary deconstruction robot is accompanied by a small mobile robot platform. The mobile robot platform observes the workspace of the deconstruction robot through a 3D LiDAR scanner. Whenever the emitted laser hits a reflective surface, it creates a point in 3D space. These scanned points then form a point cloud. The used LiDAR scanner *Ouster OS1-128* creates a 360° scan of its surroundings with a frequency of 10Hz. Each scan is analysed using image recognition technology based on YOLOv5 to detect the presence of humans. If a person is detected, their coordinates are transformed into the testbed's global coordinate system and compared with the deconstruction robot's active work space. This space corresponds to the danger zone. If the coordinates of the detected human are inside the danger zone, the mobile robot platform sends a stop command to the deconstruction robot via MQTT using a dedicated topic and the 5G connection. Additionally, the remote operator is informed of the incident via the same communication protocol but a different MQTT topic. As an additional safety layer, the operator can stop the machine remotely in case the emergency stop released by the mobile robot platform fails. Furthermore, the operator receives a notification when a human is observed in the vicinity of the active workspace, but not yet inside it (see Figure 16). The MQTT broker that handles all these messages is located on the testbed's edge server Figure 15.

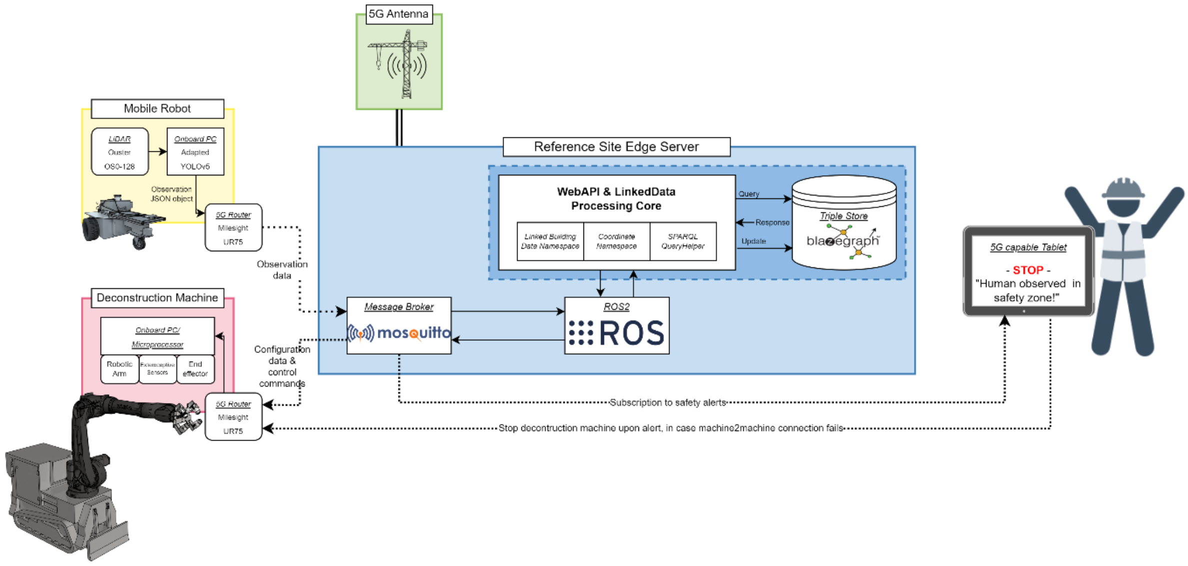

Figure 15: Communication architecture

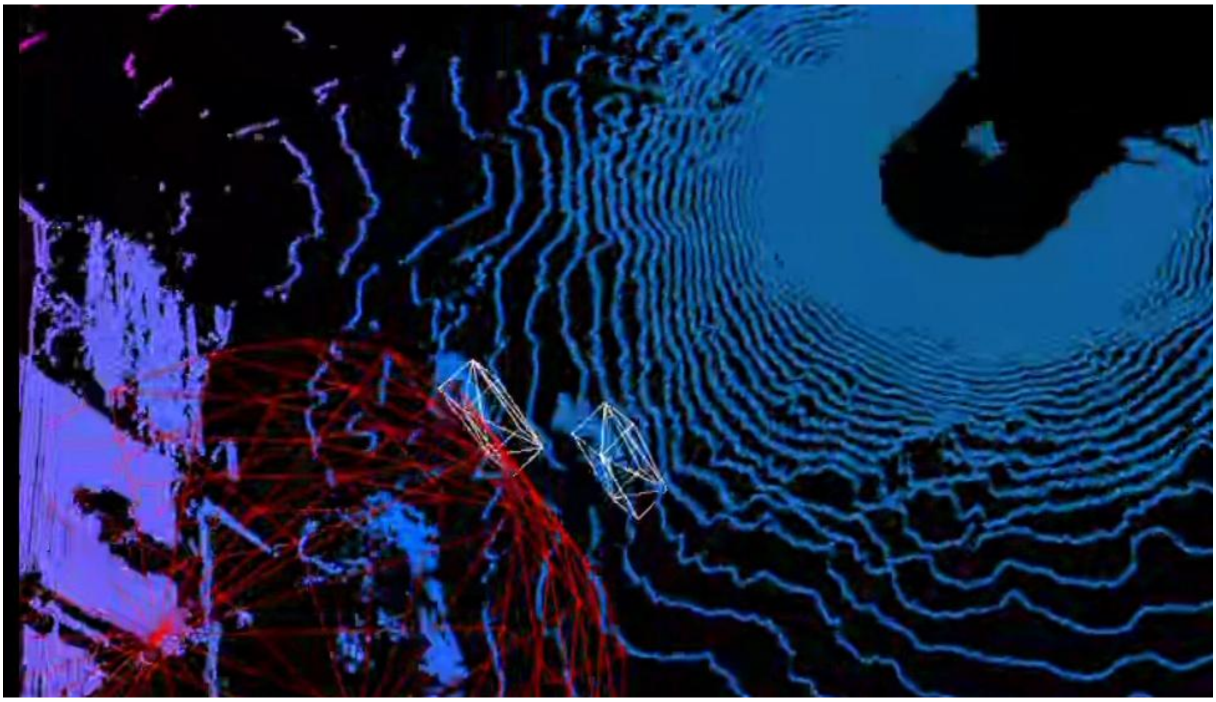

Figure 16 Environmental perception of the mobile robot platform through the LiDAR sensor. The red space marks the work space of the deconstruction robot. The white cuboids highlight humans that have been detected in the vicinity of the robot's workspace.

This use case implementation differs from the initial concept as presented in [5] where the raw point cloud was streamed via the 5G network to the edge server for centralized processing. The modification was necessary due to the limited uplink on the construction testbed. Even in its minimal resolution the scanner already produces a constant output and thus uplink of approximately 63Mbit/s. By this, a single sensor sufficed to consume more than 75% of all available network resources on the uplink.

On the one hand, the new approach relieves the load on the network significantly as the message size decreases to a few kbit/s. On the other hand, additional integrational overhead is not to be neglected. Not only was it necessary to equip the mobile robot platform with local computation hardware and power supply that needed to be purchased, mounted and integrated with the LiDAR scanner and the network device. The robots also required contextual awareness. The mobile robot platform needs to "understand" where itself and the deconstruction robot are located on site, what areas correspond to danger zones and when these are active. Furthermore, it needed to learn through which channels, and by which commands it could communicate with the deconstruction robot in case of a human observation inside the danger zone. Moreover, due to the reduced onboard processing capabilities a potentially new latency factor was introduced to the system. A detailed analysis of latency within the framework of the MAF evaluation of the use case can be found in Deliverable 9.5.

To explore the potential advantages of a higher uplink for construction use cases, as well as the technical feasibility of this, a mobile mmWave setup *Qualcomm mmW Travel Kit* was tested at the Reference Construction Site in collaboration with Qualcomm Figure 17. The test network has the following specifications:

- RAN: Sercomm NR-DC, QC FSM100 based AIO Small cells
- sub6: Tx power 23 dBm, bandwidth 100 MHz, TDD pattern DDDSU
- mmW: Tx power 23 dBm, bandwidth 4x100 MHz, 64QAM, TDD pattern DDSU
- 5G Core: Campus Genius

The test devices were:

- Qualcomm SDX65 mmW CPE reference designSub6 + mmW (800 MHz CA), high-gain directive antennas for stationary tests
- Qualcomm SM8450 MTP (Mobile Testing Platform) for walk and coverage tests

Figure 17: Qualcomm mmW Travel Kit" test equipment and setup on the construction testbed

With this test setup though it was limited in power, it had a reduced number of carriers and still downlink favouring TDD pattern, in direct line of sight 176 Mbit/s could be reached on the uplink. A theoretical calculation based on these measurement results showed that even 350Mbit/s would be achievable. This would provide sufficient resources on the uplink to transmit the point cloud scan in full resolution while leaving room for other applications. Nevertheless, as in the shared workspace of a construction site resources will always be limited. The reasonable, purpose-oriented distribution and allocation of these resources and the optimisation of data streams remain open for future research.

4 Conclusion

The Living Lab has proven to be a dynamic and productive environment, fostering collaboration and innovation across all project partners. One of the key strengths was the strong cooperation among the 27 participating FSTP entities which brought together expertise from industry in particular SMEs and academia. This diverse partnership ensured that multiple perspectives were represented, enriching both the technical and strategic dimensions of the work.

A major achievement of the Living Lab was the successful demonstration of a deconstruction use case, which showcased how 5G technology could be applied in the construction industry. Collaborating with other partners from the core consortium enabled the active sharing of expertise, technical insights and lessons learned, creating synergies between verticals. The achievements towards the MAF for the construction use cases (see WP1-IPT), the further experiments with the Meter-X device (WP3-RWTH-ACS) for energy-awareness, and the testing of the mmWave devices (Qualcomm), showcase that a collaborative approach was essential in meeting the project's milestones. It proved particularly useful for developing prototypes for proof of concept, executing trials and completing dissemination activities on time.

The developments within the deconstruction task demonstrated the feasibility of 5G integration for automated robotic deconstruction of steel frame structures by integrating mobility, perception, control, and communication within a unified system. Standardized steel connections provided a suitable foundation for automation, enabling the design of a scalable approach that preserves both structural members and fasteners for reuse in line with circular construction principles. The combination of advanced sensing, AI-driven perception, and tactile feedback allowed reliable bolt detection and removal under realistic site conditions. A custom end effector integrating camera, force–torque sensing, and impact driver was developed to carry out the unbolting process, while adaptive path planning enabled the robot to operate robustly in uncertain environments.

In the deconstruction use case, the Living Lab has demonstrated its capability to facilitate processes as outlined in tasks T5.2, T5.3, T5.4, and T5.5. The testing and evaluation of subtasks, including the development of automated deconstruction machinery, the deployment of XR for robotic assistance, and safety systems for deconstruction—were successfully conducted on modules constructed within the ReStage structure.

With the 5G network infrastructure available in the Living Lab, the user-device, robot and edge server are able to communicate with one another, allowing for cross-collaboration between independent entities. The facility enabled not only machine-to-machine communication (e.g., between robots and edge servers) but also human-to-machine interaction (e.g., between human-operated XR devices and robots).

Beyond the consortium, the Living Lab also achieved positive stakeholder engagement. External stakeholders, including policy representatives, were involved and responsive to the results, which enhanced the project's visibility and relevance in the wider ecosystem. This was further supported by high-quality dissemination efforts, including publications and participation in diverse events, ensuring impact well beyond the immediate partnership. One special event was the 2025 Open Campus Week on 26th of August, where all FSTP Partners from the second open call were presenting their project results to a range of guests from industry, politics and academia.

The Living Lab also provided the basis for evaluating the technical feasibility of network capabilities and other technical devices.

Although the work and developments in the construction vertical have yielded many successes, they also show where future research and development should focus. First and foremost, end users from verticals who have not yet had any experience with 5G should be given a lower-level access to these new technologies. This includes clear, bidirectional communication regarding the implications and consequences of certain design decisions on both the network side and the user side. Additionally, there is a need to catch up in terms of user equipment with regard to native 5G support e.g., for XR devices.

But for all that, the Living Lab successfully combined technological experimentation with strong collaboration, knowledge sharing, and stakeholder outreach, thereby fulfilling its role as a central driver of the project's success.

5 References

[1] M. Pitz, M. Zöcklein, L. Manassés Pinheiro de Souza, K. Rajpathak, A. Göppert, S. Brell-Cokcan, R. H. Schmitt und A. Monti, „Enhancing Energy Monitoring in Construction and Robotics with Plug-and-Play Solution Meter-X,“ in *Proceedings of the 2025 European Conference on Computing in Construction*, Porto, Portugal, 2025.

[2] M. Brochhaus, M. Pitz, B. Khan, P. Kehl, M. Darroudi, L. Manassés de Pinheiro Souza, M. Zöcklein und V. Jung, „Deliverable D1.1: FORWARD LOOKING USE CASES, THEIR REQUIREMENTS AND KPIS/KVIS,“ 2023.

[3] M. Brochaus, P. Kehl, P. Mohanram, L. Manassés, P. Salvati, J. Nasreddine, C. Kamp, C. H. Wu und M. Zöcklein, „Deliverable D1.2: FORWARD LOOKING USE CASES, THEIR REQUIREMENTS AND KPIS/KVIS (UPDATE),“ 2024.

[4] Fraunhofer IPT, „5G Industry Campus Europe,“ 04 09 2025. [Online]. Available: https://5g-industry-campus.com/.

[5] IT Center RWTH Aachen University, „NTP Server,“ 04 09 2025. [Online]. Available: https://help.itc.rwth-aachen.de/service/uvjppv3cuan8/.

[6] R. Nikhila, G. Valentin, H. Yuan-Ting, H. Ronghang, R. Chaitanya, M. Tengyu, K. Haitham, R. Roman, R. Chloe, G. Laura, M. Eric, P. Junting, V. A. Kalyan und C. Nicolas, „SAM 2: Segment Anything in Images and Videos,“ 2024. [Online]. Available: https://arxiv.org/abs/2408.00714.

[7] S. Liu, Z. Zeng, T. Ren, F. Li, H. Zhang, J. Yang, C. Li, J. Yang, H. Su, J. Zhu und others, „Grounding dino: Marrying dino with grounded pre-training for open-set object detection,“ in *arXiv preprint arXiv:2303.05499*, 2023.

[8] S. Stumm, E. Kerber und A. Krishnan, „Roboter-gestütztes Schweißen – Verteilte Produktionstechnik für dynamische Automatisierung,“ in *IoC - Internet of Construction*, Springer, 2024, pp. 505-565.

[9] V. Jung, C. Kamp, C. H. Wu und M. Zöcklein, „Deliverable D5.2: PROTOTYPE SYSTEM FOR CONTROLLED DECONSTRUCTION PROCESS,“ 2024.

[10] J. Oraskari, L. Kirner, M. Zöcklein und S. Brell-Cokcan, „Towards Human-machine Collaboration in Autonomous Material Handling on Construction Sites,“ *Human-Machine Communication,* 2024.

[11] L. Kirner, M. Zöcklein, J. Oraskari, C. Kamp, F. Claßen und S. Brell-Cokcan, *Loosely coupled observation processing and data exchange system for complex teams of on-site construction robots,* 2024.