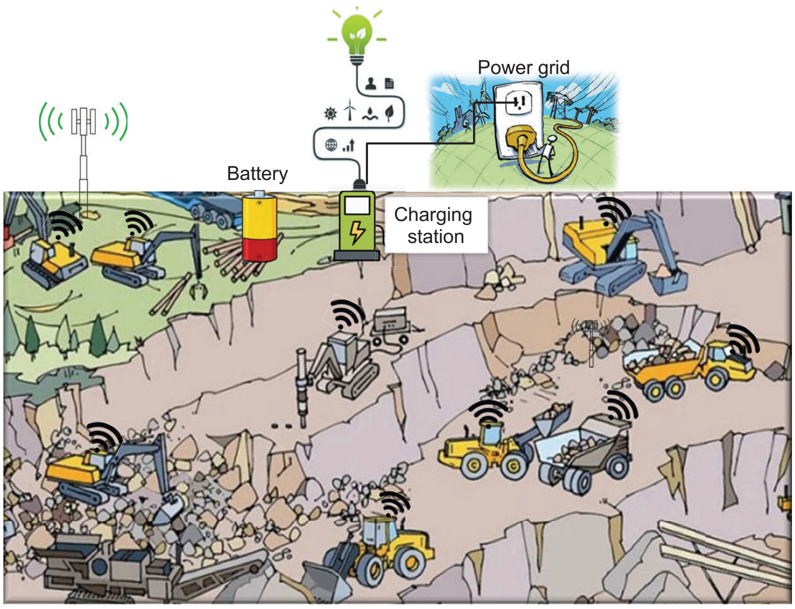
GREENER: Intelligent Energy Management in Connected Construction Sites

Public Report



Project within FFI Effektiva och uppkopplade transportsystem

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Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1. Summary

The construction industry is a key driver of economic growth and social development, generating 9% of Europe's GDP and providing 18 million jobs[1]. However, it is also a significant source of environmental damage due to emissions. Traditionally, it was slow to adopt new technologies, the industry is now advancing with the electrification of construction sites through autonomous electric machines. Yet, without proper infrastructure support, these machines may not operate optimally or realize their full potential.

The GREENER project focused on developing energy management techniques via software components in simulation environments. Our objectives were achieved through: (1) a simulation framework for modeling construction site operations, (2) optimization models for energy efficiency that integrate all consumption components, renewable energy sources, and battery storage systems, and (3) reliable wireless communication infrastructure through optimized base station placement. The project's outputs, including research papers, tools, and guidelines, aim to help the industry achieve greener construction sites. Evaluations were performed in simulations and lab settings, replicating real-world conditions, facilitating future deployments.

Simulation framework. The simulation framework includes a dynamic model to describe the longitudinal behavior of electric machines, which are used in a fleet model to evaluate transport efficiency. The fleet model uses discrete event simulation to represent the logistics of the transport operations and capture interactions between machines and resources. A case study at a quarry site in Germany demonstrates the framework's ability to determine the optimal number of machines for the operation. The simulation framework considers factors such as machine performance, charging infrastructure, and the required state of charge. The simulation framework operates on two levels: (1) the machine level and (2) the fleet level. At the machine level, a dynamic model calculates driving time and energy consumption based on road profile. At the fleet level, a discrete event simulation system models the operation logistics, using data from the machine model to assess transport efficiency. The model uses performance indicators like productivity, resource utilization, and queuing statistics. The case study showed that the simulation can effectively model the complex characteristics of transport operations and identify bottlenecks, like the loading station in the case study. The framework is intended to be a tool for decision-making in construction management, helping planners optimize operations.

Optimization model. A novel rule-based Model Predictive Control (MPC) framework, RubPC, was developed for scheduling Battery Energy Storage Systems (BESS) in microgrids under uncertain power generation and load conditions. It addresses mismatches between estimated and actual load and Renewable Energy Sources (RES) power by dividing the operation space into "white" and "yellow" zones. The white zone represents

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[1] https://single-market-economy.ec.europa.eu/sectors/construction_en

optimal operation, while the yellow zone serves as a buffer to prevent infeasible operations. MPC keeps the system in the white zone, and a rule-based controller intervenes if the system enters the yellow zone due to forecast errors, prioritizing safety and constraint satisfaction. RubPC uses a two-level control system: MPC for maintaining the white zone and rule-based control for corrective actions in the yellow zone. This approach combines MPC's optimization with the simplicity and robustness of rule-based control. Simulation results from an electrified quarry site in Germany demonstrate RubPC's effectiveness in managing uncertainties, satisfying constraints, and balancing cost with robustness. Unlike traditional Robust or Stochastic MPC, RubPC requires no prior knowledge of uncertainties and has lower computational complexity.

Placement model. This model introduces a framework for planning private 5G networks in surface mines, addressing the unique challenges posed by their ever-changing terrains. This framework uses an evolutionary algorithm to optimize the placement of both fixed base stations (BSs) and movable base stations, known as Cells on Wheels (CoWs), based on mine plans. The mine plan provides an estimate of how the terrain profile evolves over time, which is crucial for radio network planning, including the dimensioning, orientation, and location of BS antennas. The framework considers the dynamic nature of the mine environment, including the changing topography and the radio shadowing caused by heavy machinery. It also considers the need for reliable and timely communications to support autonomous equipment and remote operations in the mining industry. The proposed model uses a 3D Bresenham algorithm to assess the Line-of-Sight (LoS) conditions based on terrain maps. It also incorporates a radio model tailored for surface mines, utilizing an extension of the ITU-526 model to estimate path loss, as well as diffraction loss. The results demonstrate the effectiveness of using both fixed and movable BSs to improve connectivity in the mine surface and shows that CoWs can improve the average Signal-to-Interference & Noise Ratio (SINR) by 1 to 10 dB in certain scenarios.

The GREENER project consortium consisted of three partners, which were Mälardalen University (MDU), Volvo Construction Equipment (VCE) and the Swedish National Road and Transport Research Institute (VTI). MDU acted as the project coordinator. VCE provided competence in construction site industry, electric machines and infrastructure, VTI performed simulation modeling, and MDU contributed to optimization models and communication solutions. The project started in September 2020, and it was ended in December 2024.

2. Sammanfattning på svenska

Byggbranschen är en viktig drivkraft för ekonomisk tillväxt och social utveckling, den genererar 9 % av Europas BNP och ger 18 miljoner jobb. Det är dock också en betydande källa till miljöskador på grund av utsläpp. Traditionellt gick det långsamt att ta till sig ny teknik, industrin går nu framåt med elektrifiering av byggarbetsplatser genom autonoma elektriska maskiner. Men utan korrekt infrastrukturstöd kanske dessa maskiner inte fungerar optimalt eller realiserar sin fulla potential.

GREENER-projektet fokuserade på att utveckla energihanteringstekniker via mjukvarukomponenter i simuleringsmiljöer. Våra mål uppnåddes genom: (1) ett simuleringsramverk för modellering av byggarbetsplatser, (2) optimeringsmodeller för energieffektivitet som integrerar alla förbrukningskomponenter, förnybara energikällor och batterilagringssystem, och (3) pålitlig trådlös kommunikationsinfrastruktur genom optimerad basstationsplacering. Projektets resultat, inklusive forskningsrapporter, verktyg och riktlinjer, syftar till att hjälpa industrin att uppnå grönare byggarbetsplatser. Utvärderingar utfördes i simuleringar och labbmiljöer, replikerade verkliga förhållanden, vilket underlättade framtida implementeringar.

Simuleringsramverk. Simuleringsramverket inkluderar en dynamisk modell för att beskriva det longitudinella beteendet hos elektriska maskiner, som används i en flottmodell för att utvärdera transporteffektivitet. Flottmodellen använder diskret händelsesimulering för att representera logistiken för transportverksamheten och fånga interaktioner mellan maskiner och resurser. En fallstudie vid en stenbrottsplats i Tyskland visar ramverkets förmåga att bestämma det optimala antalet maskiner för verksamheten. Simuleringsramverket tar hänsyn till faktorer som maskinens prestanda, laddningsinfrastruktur och det erforderliga laddningsläget. Simuleringsramverket fungerar på två nivåer: (1) maskinnivå och (2) flottnivå. På maskinnivå beräknar en dynamisk modell körtid och energiförbrukning utifrån vägprofil. På flottnivå modellerar ett diskret händelsesimuleringssystem driftlogistiken, med hjälp av data från maskinmodellen för att bedöma transporteffektiviteten. Modellen använder resultatindikatorer som produktivitet, resursutnyttjande och köstatistik. Fallstudien visade att simuleringen effektivt kan modellera de komplexa egenskaperna hos transporter och identifiera flaskhalsar, som laststationen i fallstudien. Ramverket är tänkt att vara ett verktyg för beslutsfattande inom byggledning och hjälpa planerare att optimera verksamheten.

Optimeringsmodell. Ett nytt regelbaserat Model Predictive Control (MPC) ramverk, RubPC, utvecklades för att schemalägga batterienergilagringssystem (BESS) i mikronät under osäkra kraftgenererings- och belastningsförhållanden. Den tar itu med bristande överensstämmelse mellan beräknad och faktisk belastning och kraft från förnybara energikällor (RES) genom att dela upp driftsutrymmet i "vita" och "gula" zoner. Den vita zonen representerar optimal drift, medan den gula zonen fungerar som en buffert för att förhindra omöjliga operationer. MPC håller systemet i den vita zonen, och en regelbaserad styrenhet ingriper om systemet går in i den gula zonen på grund av prognosfel, vilket prioriterar säkerhet och tillfredsställelse av begränsningar. RubPC använder ett kontrollsystem på två nivåer: MPC för att upprätthålla den vita zonen och regelbaserad kontroll för korrigerande åtgärder i den gula zonen. Detta tillvägagångssätt kombinerar MPC:s optimering med enkelheten och robustheten hos regelbaserad kontroll. Simuleringsresultat från en elektrifierad stenbrottsplats i Tyskland visar RubPC:s effektivitet när det gäller att hantera osäkerheter, uppfylla begränsningar och balansera kostnad med robusthet. Till skillnad från traditionell Robust eller Stokastisk MPC kräver RubPC inga förkunskaper om osäkerheter och har lägre beräkningskomplexitet.

Placeringsmodell. Denna modell introducerar ett ramverk för planering av privata 5G-nätverk i ytgruvor, och tar itu med de unika utmaningar som deras ständigt föränderliga terräng utgör. Detta ramverk använder en evolutionär algoritm för att optimera placeringen av både fasta basstationer (BS) och rörliga basstationer, kända som Cells on Wheels (CoWs), baserat på gruvplaner. Gruvplanen ger en uppskattning av hur terrängprofilen utvecklas över tiden, vilket är avgörande för planering av radionätverk, inklusive dimensionering, orientering och placering av BS-antenner. Ramverket tar hänsyn till gruvmiljöns dynamiska natur, inklusive den föränderliga topografin och radioskuggningen som orsakas av tunga maskiner. Den överväger också behovet av tillförlitlig och snabb kommunikation för att stödja autonom utrustning och fjärroperationer inom gruvindustrin. Den föreslagna modellen använder en 3D Bresenham-algoritm för att bedöma siktlinjeförhållandena (LoS) baserat på terrängkartor. Den innehåller också en radiomodell som är skräddarsydd för ytminor, som använder en förlängning av ITU-526-modellen för att uppskatta vägförluster, såväl som diffraktionsförluster. Resultaten visar effektiviteten av att använda både fasta och rörliga BS:er för att förbättra anslutningsmöjligheterna i gruvytan, och visar att CoWs kan förbättra den genomsnittliga Signal-to-Interference & Noise Ratio (SINR) med 1 till 10 dB i vissa scenarier.

Projektkonsortiet GREENER bestod av tre partners, vilka var Mälardalens högskola (MDU), Volvo Construction Equipment (VCE) och Statens väg- och transportforskningsinstitut (VTI). MDU fungerade som projektkoordinator. VCE tillhandahöll kompetens inom byggarbetsplatsindustrin, elektriska maskiner och infrastruktur, VTI utförde simuleringsmodellering och MDU bidrog till optimeringsmodeller och kommunikationslösningar. Projektet startade i september 2020 och avslutades i december 2024.

3. Background

Swedish energy policies aim to promote ecological sustainability, competitiveness and security of supply, which is based on lawmaking within the EU. The EU aims to reduce energy consumption by 32.5%, while achieving 32% of energy consumption provided from renewable sources. Sweden aims at 50% more energy efficiency by 2030 compared to 2005, and 100% of electricity production shall be from renewable sources by 2040 [1]. In 2017, 58% of Swedish electricity generation originated from renewable energy sources such as hydropower, wind power, biofuels and solar power. A significant portion (over 80%) of today's energy is still produced from brown sources [2]. The industrial sector accounts for using about 30% of fossil fuels, while transport sector is using about 80% of fossil fuels. It is extremely important to have strategies to reduce fossil fuels in both industrial and transportation sectors. Construction sites reside in both industrial and transport sector, and there is a trend that machines are becoming electric. Electrifying construction sites might be insufficient to reduce carbon emission since the power grid may rely on fossil fuels to generate electricity. However, the unpredictability and capital cost are two major factors preventing the widespread use of renewable energy in industry. With the help of microgrid [3], distributed renewable energy sources located in the same area can now be effectively integrated to provide power to local users with less power transmission and distribution infrastructure and match the dynamic local demand with local supply in a more convenient way.

Internet of Things (IoT) [4] is an effective communication framework that is gradually adopting in industrial scene. The IoT is a paradigm that promotes ubiquitous and pervasive computing scenarios with interconnection of sensors, actuators, and other types of small devices through wireless and wired connections. The rapid growth in the use of IoT devices will certainly produce large amounts of data, which needs to be processed and stored for use by end user applications. Conventionally, IoT devices were supposed to send their measurements to the cloud, where data centers with strong processing capabilities were able to process on big data. However, due to the constraints in channel bandwidth of local networks, and the need to support real-time applications, a new paradigm of Edge computing [5] has emerged that brings computation and storage closed to the end users. This new architecture has significant impact on data transmission latency as well as increasing network reliability. Currently, significant research efforts are focused on improving the features of flexibility, scalability, security, programmability, and real-time processing of edge computing systems so as to cope better with IoT applications. We believe that IoT and Edge computing technologies are key enablers of future energy efficient applications.

In this project, we have a strong motivation on providing an energy management framework, where it is possible to reduce energy consumption in connected electric sites by applying energy management solutions proposed at the GREENER project. The system architecture considers designing and developing smart electric construction sites that are interconnected through edge devices. This novel system architecture collects measurements locally on all machines and the edge device that resides at the construction site. The integration of Edge computing and microgrid increases the effectiveness and utilization of energy resources. This integration reinforces the sustainability of both microgrid and edge computing, since it is tightly coupled with an energy management approach that enables efficient interaction and collaboration between the different actors involved. This allows the information of power consumption to be exchanged in a timely manner. The designed optimization strategies, running on the interconnected edge devices, can take real-time decisions on how to distribute and store energy among the different devices, while maximizing the machine productivity.

To control energy consumption, the construction site needs more understanding about its operations. It needs to analyze equipment and processes to uncover inefficiencies and establish parameters for greater energy control. The IoT is helping these operators spearhead better strategies to increase productivity while preventing their energy consumption from getting out of control. The IoT basically involves a vast number of sensors connected to Internet, while sharing the data without human interaction. Having a steady, reliable and real-time data collection is of paramount importance. This will in turn affect the energy management and the business strategies. When combining IoT with energy consumption analysis, operations can implement cost-effective energy management procedures to cut back on waste while optimizing daily processes. However, the electricity generated by the power grid is partially produced from renewable energy. This project is aiming to (i) reduce energy consumption at the site, and (ii) consume energy preferably from the renewable sources of energy that are installed locally. Here, we focus on an electric site which is powered by both power grid and microgrid. In this case, the site is equipped with local energy storage that can be recharged by available local renewable energy sources, such as solar or wind power, but also by the grid if the renewable energies are insufficient. A switch panel monitors the status of the local battery storage and manages the charging of the battery from the local renewable source or from the power grid. The priority is to charge the local battery storage with locally available renewable energy so local demand will be largely met by local battery storage.

4. Purpose, research questions and method

The purpose of this project was to devise solutions for energy management in electric construction sites, targeting simulation models, optimization approaches, and network management through reliable communication. The main research questions addressed by this project were:

- RQ1. Is it possible to model a simulation framework for operations in a construction site using electric machines?
- RQ2. How to devise an energy efficient solution for an electric construction site by optimizing charging and discharging schedules.
- RQ3. How to provide connectivity and reliable communication in a dynamic environment of a construction site, where machines are constantly moving, and the site is continuously changing?

To address RQ1, a simulation framework for modelling the transport operations using electric construction machines was proposed. A fleet simulation system is designed using discrete event simulation technique to represent the logistics of the transport operations and capture the interactions between machines and various facilities at the worksite. For RQ2, we proposed RubPC, which is a novel rule-based model predictive control (MPC). We partitioned the feasible operation space of the system into two subzones, referred to as the white and yellow zones. We validated RubPC by using data from an electrified quarry site in Germany. To address RQ3, we have devise several approaches for mobility management in a wireless domain, including (i) SDMob, a software defined networking based solution for wireless communication in a construction site providing a centralized mobility management, (ii) RPL-RP, an RPL (standard routing protocol for IoT networks) with route projection, where it provides transversal routing, which is very effective when conventional routing approaches may fail, (iii) ACTOR, an adaptive control of transmission power in low-power wireless networks that dynamically optimized transmission power of wireless devices in order to provide a reliable communication, and (iv) an optimization framework for deployment of private broadband networks in a construction site in order to provide reliable connected network in a constantly changing environment of a construction site.

For details and more discussions on the developed methods, please refer to the published articles.

5. Objective

In this project, we aimed to design energy management solutions for a connected and electric construction site. Designing a simulation framework, optimization models for energy efficiency, and reliable wireless communication solutions are among key objectives of this project. The main objectives of the project that were achieved through the project are described below.

O1. Design and develop models for heavy machines and site logistics at the construction site in a simulation tool to provide the possibility of imitating the real scenario. Simulation is chosen for modelling the site operations because it provides realistic representations of interactions among the systems' various components while accounting for key uncertainties in the operating environment.

O2. Design of a comprehensive energy management system for electro-mobility, focusing on three main levels: (i) the component level (ii), the energy site level, and (iii) the fleet management level. The component level focuses on the design of a distributed local DC smart grid to deploy within the electric site, to enable a more flexible management of the electric energy; The site level considers the set of all the electrical components, the batteries, and the machine demands to formulate a multi-agent optimization problem, for the overall energy management of the electric site. Finally, the fleet management level optimizes the operation of the electric machines to distribute the workload, minimizing their electricity demand, and adjusting it to match the required production.

O3. Design and develop an edge computing system architecture, where all the data are stored and processed locally at the Edge device. This incorporates designing a software defined networking (SDN) controller component to communication with all wireless sensors attached on machines. SDN controller orchestrates and manages the network by providing a reliable communication over wireless channel through traffic adaptive, channel hopping and resource management techniques.

6. Results and deliverables

The objectives of the project have been achieved through devising several solutions and publishing the results in conferences and open-source journals. The main results are explained briefly in this section.

R1. Results on simulation framework. A comprehensive simulation framework for modeling off-road transport operations at construction sites using electric construction machines has been proposed. The framework integrates machine dynamics and fleet-level logistics through discrete event simulation, capturing interactions among machines and resources while considering key uncertainties. A case study conducted at a quarry site in Germany demonstrates the framework's ability to optimize fleet size for efficient transport operations. As illustrated in Figure 1, the simulation framework models a transport operation consisting of loading, transport, dumping, and charging processes. Results show that the framework successfully models machine behavior, estimates energy consumption, and evaluates transport efficiency, ultimately supporting decision-making for construction site management [6]. Notably, the study identifies the loading station as the system's bottleneck, and simulation results indicate that a fleet of six electric machines achieves maximum productivity of 317 transport cycles per shift, compared to 312 cycles with five machines. The queuing time at the loading station increases significantly from 2.86 seconds to 86.03 seconds when increasing the fleet from five to six machines, confirming the capacity limitation.

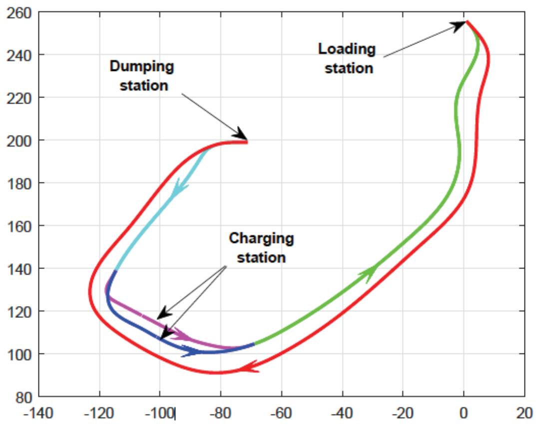

Figure 1. Site layout. The transport paths are illustrated using different colors.

The contributions of this work align closely with the research project objective of designing and developing models for heavy machines and site logistics in a simulation tool to replicate real-world scenarios [7]. By implementing a dynamic model at the machine level and a discrete event simulation at the fleet level, the framework realistically represents the interactions among system components and accounts for environmental uncertainties [6]. Quantitative results show that machine energy consumption is significantly influenced by road gradients, with the highest energy usage occurring on a steep uphill section (~20%) of the transport route (Figure 2). The study also highlights that charging infrastructure is not a bottleneck in the operation, as the charging station utilization remains low. These findings validate the use of simulation for site operations, confirming its role in optimizing resource allocation and enhancing decision-making.

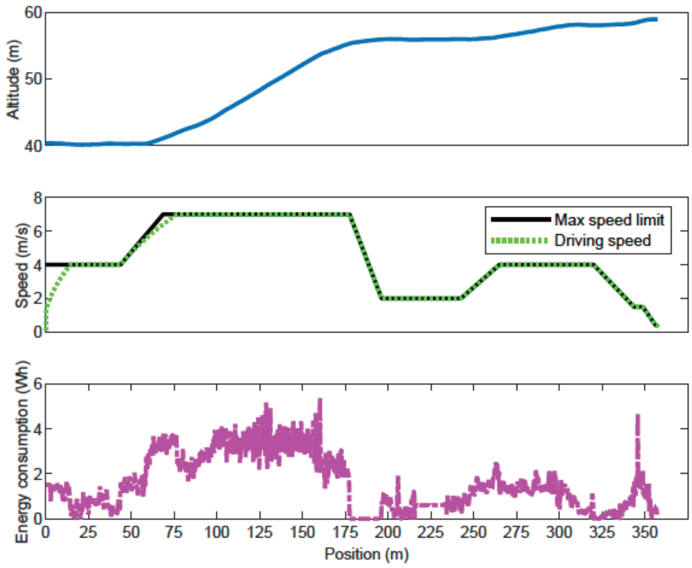

Figure 2. Result from machine simulation for the transport path from loading station to dumping station (path in red in Figure 1). Top: altitude of the transport path. Middle: The maximum speed limit and the calculated driving speed. Bottom: energy consumption.

R2. Results on optimization model. We presented RubPC, a novel rule-based predictive control framework for battery scheduling in microgrids, addressing uncertainties in power generation and load demand. The proposed approach partitions the microgrid's operation space into distinct white and yellow zones, ensuring safe operation through a supervisory rule-based controller. By combining the optimization capability of Model Predictive Control (MPC) with the robustness of rule-based methods, RubPC effectively prevents constraint violations due to forecasting errors while reducing reliance on prior knowledge of uncertainties. The architecture of the proposed control system is illustrated in Figure 3, where the microgrid integrates a Battery Energy Storage System (BESS), renewable energy sources, and industrial loads.

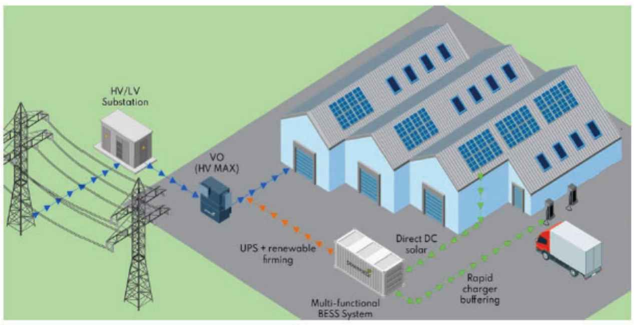

Figure 3. Simplified architecture of worksite microgrid.

A case study conducted at an electrified quarry site in Germany, equipped with a BESS and solar panels, demonstrates that RubPC reduces daily electricity costs while maintaining power exchange and battery state of charge (SoC) within safe limits. Specifically, Figure 4 shows that RubPC achieves a 13% reduction in daily energy costs compared to traditional rule-based control and closely matches the performance of MPC, which achieves the lowest cost.

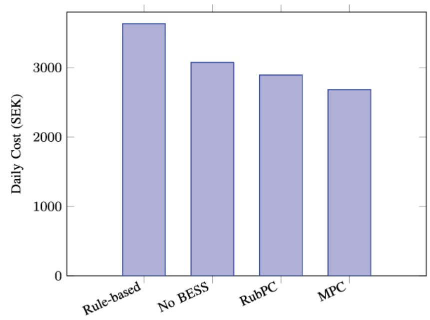

Figure 4. Comparison of the daily electrical energy cost using RubPC, MPC, and Rule-based control.

A key finding of the study is highlighted in Figure 5, which compares the power exchange with the grid and the battery's SoC across different control strategies. The results reveal a major drawback of conventional MPC, which fails to maintain the power flow within safe limits. Specifically, the grid power flow, which should not exceed 700 kW, peaks at 812 kW under MPC, violating the operational constraints and potentially causing severe financial penalties or infrastructure overload. In contrast, RubPC effectively keeps the grid power flow within the allowable limits, ensuring safe and stable operation. The figure also demonstrates how the battery's SoC remains within the designated white zone when using RubPC, whereas conventional MPC risks pushing it into critical levels due to forecast inaccuracies. Meanwhile, the rule-based control method maintains safety but lacks the cost efficiency of RubPC, as it fails to optimize battery usage dynamically.

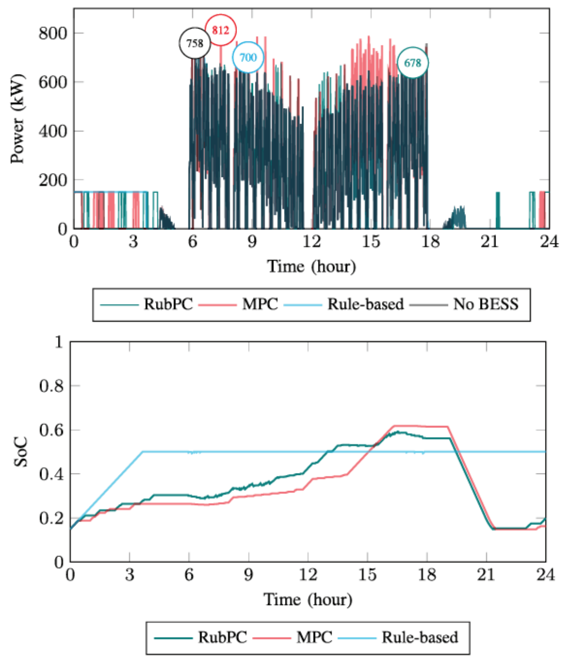

Figure 5. Power flow with the grid (top) and the SoC of the BESS unit (bottom).

The contributions align with the research project objective of designing a comprehensive energy management system for electro-mobility. At the component level, RubPC implements dynamic charge and discharge control, effectively managing energy flow akin to a local DC smart grid for flexible electricity distribution. At the site level, the RubPC algorithm optimizes power exchange, integrating all electrical components, battery storage, and renewable energy sources to formulate a robust multi-agent optimization problem. At the fleet management level, RubPC ensures optimal operation of electric construction machines, dynamically adjusting power demand to minimize peak loads and distribute workload efficiently, as demonstrated in Figure 1, which illustrates the transport operation layout at the quarry site. Monte Carlo simulations further validate RubPC's robustness, confirming its ability to handle uncertainties in renewable energy generation and industrial load demand, as seen in Figure 6, where the probability distributions of power flow and SoC remain within acceptable limits. These results confirm that RubPC is a viable solution for enhancing industrial electro-mobility, reducing electricity costs, and ensuring operational reliability in uncertain environments.

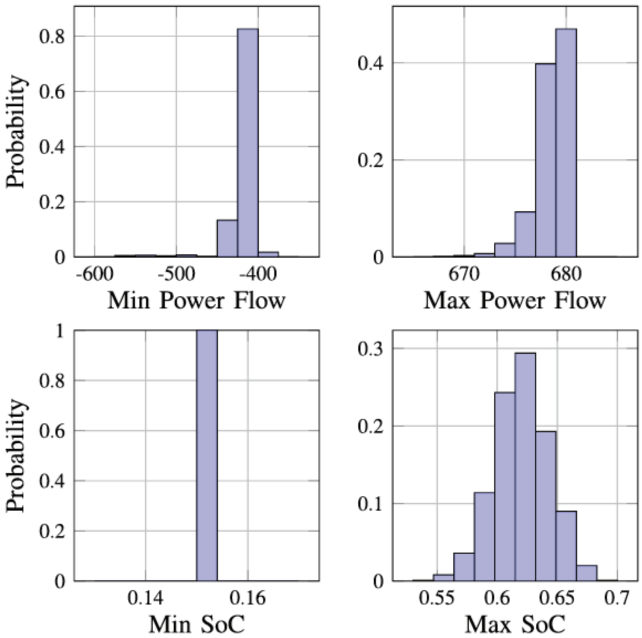

Figure 6. Probability distribution functions for the minimum and maximum grid power flow (top) and the minimum and maximum SoC of BESS unit (bottom) in 1000 Monte Carlo simulations.

R3. Results on reliable communication.

R3.1. Placement model. The project presented an optimization framework for deploying private 5G networks in surface mines, addressing the challenges posed by the dynamic and harsh mining environment. We have opted to use open pit mine for this work as it shows more complex environment, and thus requiring more radio dynamics. The framework leverages mine planning data to optimize the placement of both fixed and movable base stations (BSs), ensuring reliable and efficient communication. The major contributions include the formulation of an optimization problem for long-term radio network planning based on evolving terrain data, the incorporation of 5G-specific propagation models, and the demonstration of the effectiveness of deploying fixed and movable BSs to improve connectivity. The results show that the proposed framework significantly enhances the average Signal-to-Interference & Noise Ratio (SINR) by up to 10 dB in certain scenarios, thereby improving network reliability and performance (Figure 7).

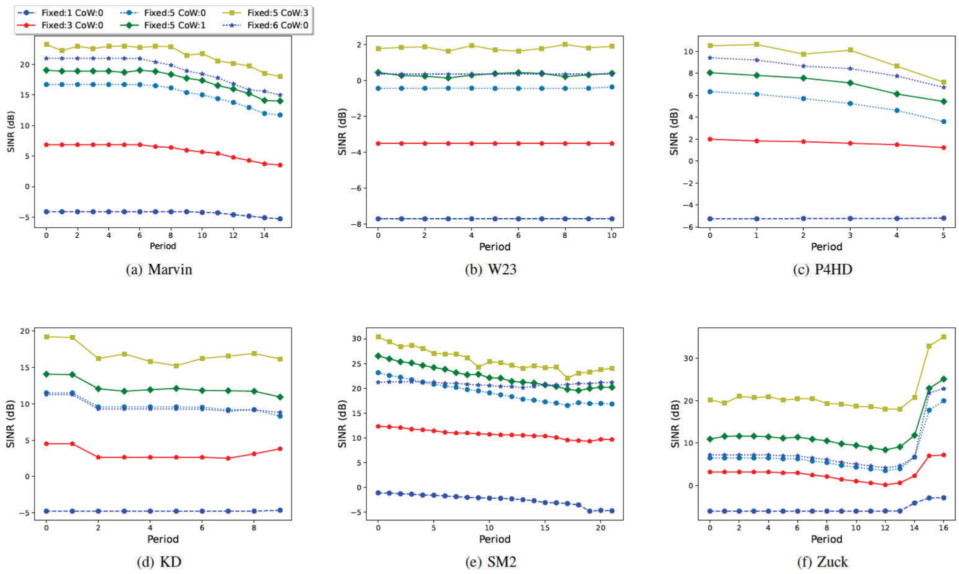

Figure 7. Average SINR in time for the mines in time.

Simulation evaluations highlight the benefits of using Cell on Wheels (CoWs) in conjunction with fixed BSs to adapt to the changing topography of the mine. For instance, in the Marvin mine, the SINR improved from 5 dB to 15 dB when using a combination of 5 fixed BSs and 3 CoWs (Figure 7a). Figures 8 and 9 illustrate the evolution of the mine's terrain over time and the optimized positions of the BSs. The implementation of the proposed framework demonstrates substantial improvements in network coverage and SINR, validating the approach's effectiveness. The results successfully achieve the objective of designing and developing edge-enabled solutions that provide connectivity in a dynamic construction site environment.

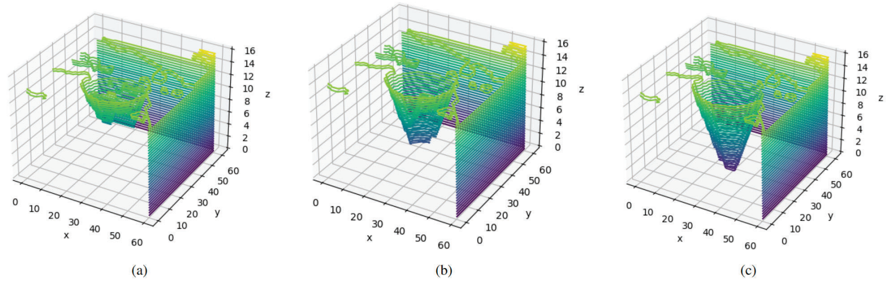

Figure 8. Marvin mine getting deeper and wider over time; (a) period 1, (b) period 5, and (c) period 8.

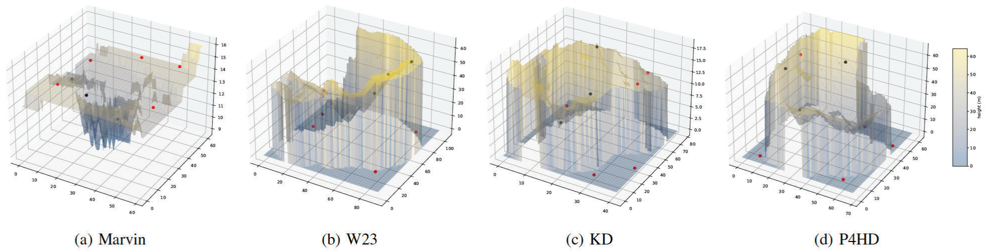

Figure 9. Snapshots of the initial states of the mines and the deployment of fixed BSs in (a) Marvin (b) W23 (c) KD and (d) P4HD mines. The red and blue dots represent the fixed BSs and CoWs, respectively.

R3.2. Adaptive Transmission Power for Reliable Communication. ACTOR, an adaptive control of transmission power in RPL, adapts transmission power using reinforcement learning, demonstrates significant improvements in network performance across various scenarios. The experimental results indicate that ACTOR achieves a higher packet delivery ratio (PDR) by nearly 20% compared to standard RPL and selected benchmarks, while also reducing the transmission power of nodes by up to 10 dBm, as shown in Figure 10a. These enhancements are accompanied by a more stable network topology with significantly fewer parent switches, which is crucial for maintaining reliable communication in dense networks.

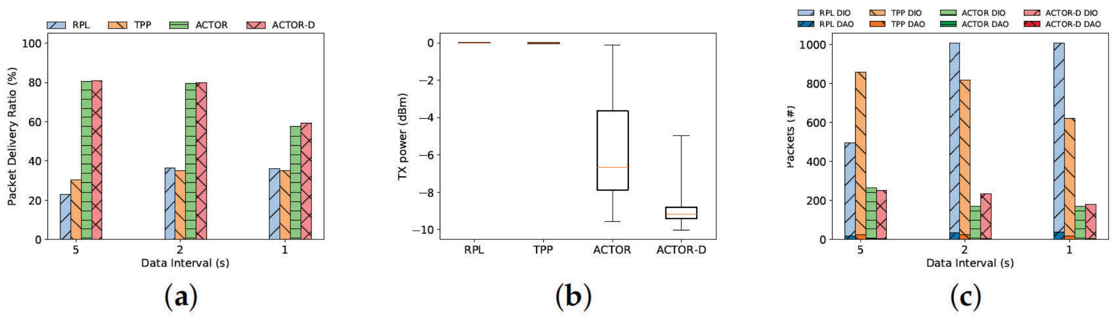

Figure 10. Experiment results for the 40-node scenario show ACTOR outperforming the benchmarks at different data intervals showing: (a) Packet Delivery Ratio, (b) Average transmission power, and (c) Routing overhead.

In simulations conducted across seven different scenarios, ACTOR showed improvements in end-to-end delay, packet delivery, and energy consumption by up to 50%, particularly evident in dense and high-traffic conditions (Figure 11a). For instance, in the 40-node experiment, ACTOR outperformed both RPL and TPP, achieving a PDR of approximately 80% at higher traffic loads, whereas RPL and TPP delivered around 60% and 70%, respectively (Figure 10a). Additionally, ACTOR successfully reduced the average transmission power to -7.39 dBm, contrasting sharply with RPL's constant 0 dBm (Figure 10b). Furthermore, the routing overhead was minimized, with ACTOR generating fewer control packets compared to RPL and TPP, as illustrated in Figure 11c. These findings underscore the effectiveness of ACTOR in optimizing transmission power settings dynamically, thereby enhancing overall network efficiency and reliability.

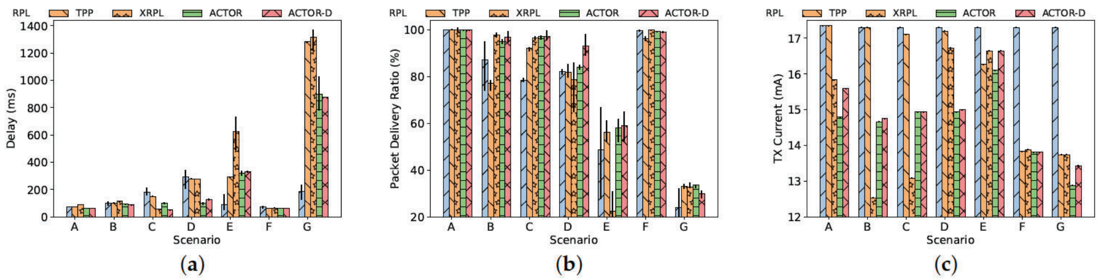

Figure 11. Simulation results considering seven different scenarios showing: (a) End-to-end delay, (b) Packet Delivery Ratio, and (c) the current used for radio transmission.

R3.3. Edge-enabled Mobility Management in Wireless Networks. SDMob, a software-defined networking (SDN)-based architecture for mobility management in IoT networks, leverages an external controller to enhance the performance of mobile nodes in RPL-based networks. Figure 12 illustrates the basic and enhanced versions of SDMob, highlighting how the architecture evolves to support multiple mobile nodes, high-density anchor deployments, and more realistic mobility patterns through mechanisms like smart buffer management and congestion timers. The enhanced SDMob significantly improves performance metrics such as packet delivery ratio (PDR), localization accuracy, and end-to-end delay compared to standard RPL and benchmarks like ARMOR. By offloading computation-intensive tasks like filtering algorithms to the edge device, SDMob ensures seamless handoffs while maintaining reasonable communication overhead. For instance, in scenarios with varying numbers of mobile nodes and traffic loads, SDMob outperforms RPL by nearly 20% in PDR while reducing the transmission power of nodes by up to 10 dBm , as shown in Figure 13a . These improvements are attributed to efficient handling of control traffic and proactive handoff mechanisms.

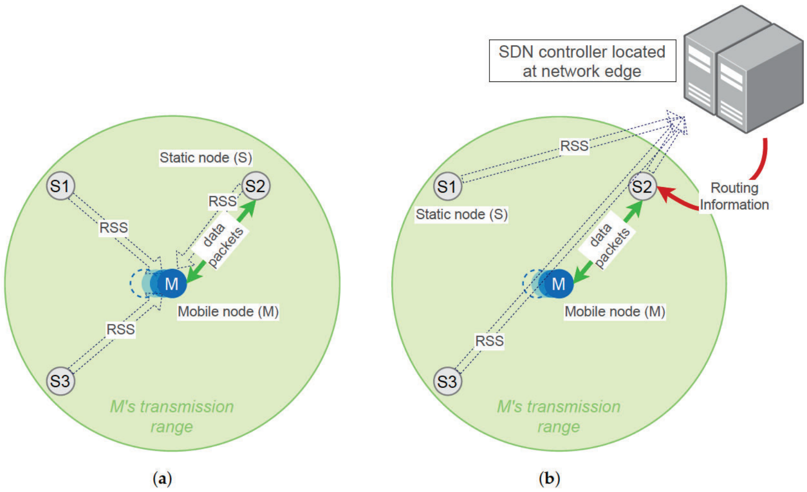

Figure 12. Illustration of mobility management strategies—(a) Distributed strategy Mobile node (M) does the routing function by processing the Received Signal Strength (RSS) values from neighboring. Static nodes (S); and (b) Centralized strategy—SDN controller at network edge picks the next best parent for M to relay data packets.

The results from simulations reveal that SDMob achieves near 100% PDR in scenarios with limited numbers of mobile nodes, while maintaining sub-meter localization accuracy under random mobility patterns and varying network topologies, as depicted in Figure 13b. However, as the number of mobile nodes increases, the control traffic also rises, leading to slight degradation in performance due to congestion. Despite this, SDMob's particle filter demonstrates resilience, converging effectively even after missing RSSI reports. In contrast, RPL shows an increasing trend in PDR with more mobile nodes due to frequent DIO transmissions, which congest the network and increase end-to-end delay.

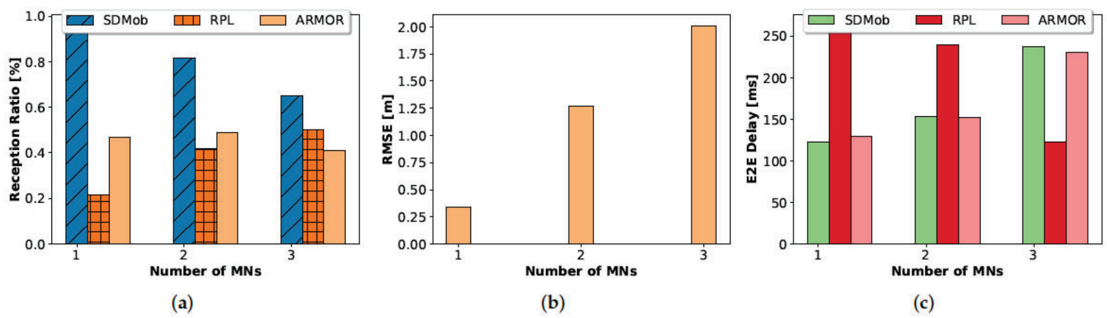

Figure 13. Simulation results for increasing number ofMNswith different solutions—(a) PDR; (b) localization error; and (c) end-to-end delay.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Results and discussions were concluded in increased knowledge and sharing for both academia and industry. Solutions are publicly available in GitHub, and papers are published with open access.
Be passed on to other advanced technological development projects	X	The project has been in collaboration with other R&D projects. The proposed methods and solutions developed in this project can be reused in other similar projects.
Be passed on to product development projects	X	The project results for energy management have been shared with VCE that can be used for product development.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

The project has resulted into the following publications:

1. Rabet, Iliar,” Mobility Support in Fog-Assisted IoT Networks”, Licentiate Thesis (2022).
2. Rabet, Iliar,” Reliable Low-Power Wireless Networks in Dynamic Environments”, PhD Thesis (2025).
3. Kaheni, Mojtaba, Jiali Fu, and Alessandro V. Papadopoulos. "Rule-Based Predictive Control for Battery Scheduling in Microgrids Under Power Generation and Load Uncertainties." IEEE Transactions on Automation Science and Engineering (2024).
4. Kaheni, Mojtaba, Alessandro V. Papadopoulos, Elio Usai, and Mauro Franceschelli. "A Privacy-Preserving Distributed Greedy Framework to Desynchronize Power Consumption in a Network of Thermostatically Controlled Loads." IEEE Transactions on Control Systems Technology (2024).
5. Rabet, Iliar, Hossein Fotouhi, Mário Alves, Maryam Vahabi, and Mats Björkman. "ACTOR: Adaptive Control of Transmission Power in RPL." Sensors 24, no. 7 (2024): 2330.
6. Kaheni, Mojtaba, Martina Lippi, Andrea Gasparri, and Mauro Franceschelli. "Selective Trimmed Average: A Resilient Federated Learning Algorithm with Deterministic Guarantees on the Optimality Approximation." IEEE Transactions on Cybernetics (2024).

7. Kaheni, Mojtaba, Elio Usai, and Mauro Franceschelli. "Resilient and privacy-preserving multi-agent optimization and control of a network of battery energy storage systems under attack." IEEE Transactions on Automation Science and Engineering (2023).
8. Rabet, Iliar, Shunmuga Priyan Selvaraju, Hossein Fotouhi, Mário Alves, Maryam Vahabi, Ali Balador, and Mats Björkman. "SDMob: SDN-based mobility management for IoT networks." Journal of Sensor and Actuator Networks 11, no. 1 (2022): 8.
9. Rabet, Iliar, Hossein Fotouhi, Mário Alves, Jaya Prakash Champati, James Gross, Maryam Vahabi, and Mats Björkman. "A Stochastic Network Calculus Model for TSCH Schedulers." In 2024 IEEE Symposium on Computers and Communications (ISCC), pp. 1-7. IEEE, 2024.
10. Rabet, Iliar, Inés Álvarez, Hossein Fotouhi, and Mohammad Ashjaei. "Demo Abstract: Towards Interoperability in a Hybrid TSN/6TiSCH Network." In Proceedings of the 21st ACM Conference on Embedded Networked Sensor Systems, pp. 500-501. 2023.
11. Rabet, Iliar, Hossein Fotouhi, Mário Alves, Maryam Vahabi, and Mats Björkman. "On the Deployment of Private Broadband Networks in Surface Mines." In 2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1-8. IEEE, 2023.
12. Rabet, Iliar, Shunmuga Priyan Selvaraju, Mohammad Hassan Adeli, Hossein Fotouhi, Ali Balador, Maryam Vahabi, Mário Alves, and Mats Björkman. "Pushing IoT mobility management to the edge: granting RPL accurate localization and routing." In 2021 IEEE 7th World Forum on Internet of Things (WF-IoT), pp. 338-343. IEEE, 2021.
13. Rabet, Iliar, Hossein Fotouhi, Maryam Vahabi, Mário Alves, and Mats Björkman. "RPL-RP: RPL with route projection for transversal routing." In 2021 IEEE 7th World Forum on Internet of Things (WF-IoT), pp. 344-349. IEEE, 2021.

8. Conclusions and future research

We have made good progress toward the project’s objectives. Through this work, we have developed simulation models for heavy machines and site logistics at construction sites, aiming to provide realistic representations of real-world operations. By incorporating simulation techniques, we captured complex interactions among various system components while accounting for uncertainties in the operating environment. Furthermore, a comprehensive energy management system was designed for electro-mobility, addressing three key levels: component level, site level, and fleet management level. At the component level, a distributed local DC smart grid was developed to enable flexible energy management. The site-level optimization considered electrical components, batteries, and machine energy demands, formulating a multi-agent optimization problem for efficient energy distribution. At the fleet level, an optimized workload distribution strategy was proposed to minimize electricity demand while ensuring production efficiency. Additionally, an edge-enabled IoT network was designed to locally manage a network of sensors in a construction site, enhancing real-time decision-making. A Software-Defined

Networking (SDN) controller was integrated to manage wireless communication, ensuring reliable data transmission through traffic adaptation, channel hopping, and resource management techniques. Overall, the outcomes of this project provide valuable insights into improving operational efficiency, energy optimization, and reliable communication in construction sites employing electro-mobility solutions.

To further enhance the proposed solution, future work will focus on improving the simulation models by incorporating additional real-time data and enabling two-way communication between the simulation tool and real-world experiments. This will facilitate the development of a digital twin of construction operations, allowing for more accurate modeling, monitoring, and optimization. In terms of energy management, future efforts will explore the integration of renewable energy sources, the implementation of real-time predictive analytics, and the adaptation of the system to more complex and diverse construction site scenarios. These enhancements aim to improve sustainability and efficiency across various operational settings. To further enhance reliable communication, we will develop AI-driven network orchestration to improve flexibility, scalability, and adaptability in dynamic construction environments. Additionally, federated learning approaches will be devised to enable distributed intelligence at the edge, while integrating localization, sensing, and communication to create a more responsive and intelligent network infrastructure.

9. Participating parties and contact persons

The project consortium consisted of three partners, including Mälardalen University (MDU), Volvo Construction Equipment (VCE), and the Swedish National Road and Transport Research Institute (VTI), where MDU was the project coordinator.

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