ASPECT –

A System for Electric and Connected Transport Solutions

Public report

Project within Energy & environment – fossil free mobile machines

Authors: Cecilia Wendin, Marcus Wilhelmsson, Carl Toller Melén, Raj Jiten Machchhar, Daniel McGillivray, Annika Ericson, Tomas Bergqvist, Beatriz Cabrero-Daniel, Viktor Kasimir, Torkel Danielsson

Date 2024-09-16

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.

For more information: www.ffisweden.se

1 SUMMARY

ASPECT builds on the findings from the Autonomous Electric Quarry project (Energimyndigheten dnr 2015-003982), where an autonomous electric fleet and other electric machines were deployed in a Swedish quarry, demonstrating significant reductions in tailpipe greenhouse gas (GHG) emissions and energy usage. Autonomy in transport solutions can be a key enabler for electrification in the mining and quarry industry, particularly through the "Elephants to Ants" approach. The concept involves replacing larger diesel-driven haulers with numerous smaller electric haulers operating autonomously as a fleet. Autonomous haulers eliminate additional driver costs and address safety and driver availability issues, a key enabler for a “Elephants to Ants”-transition. This approach provides Volvo with an opportunity to enter the mining segment, currently dominated by large machines from non-Swedish automotive OEMs.

The primary purpose of the ASPECT project has been to contribute to a comprehensive electric and autonomous transport solution that is energy-efficient, scalable, sustainable, and reliable. By operating machines and vehicles as one system, the overall site process can be optimized, creating value and minimizing waste across the entire transport solution, rather than just in individual machines and vehicles.

The Volvo autonomous transport solution is at the cutting edge of technological innovation, necessitating close collaboration among the automotive, telecommunications, and mining and quarry industries to develop a robust and scalable industrialized system. Partnering also with academic institutions offers new insights into areas where the industry has had less opportunity to focus.

Through this project, the ASPECT consortium—comprising Volvo Autonomous Solutions, Volvo Construction Equipment, Voysys, Telia, Ericsson, Blekinge Tekniska Högskola, and Göteborg University—has bolstered Swedish expertise in the research, development, and innovation of connected, electric, and autonomous transport systems. We have generated valuable data and knowledge that enhance the overall level of innovation and international competitiveness in this field. Moreover, we have expanded our network, established new partnerships, and created opportunities for future collaborations.

The project has advanced Volvo’s autonomous electric transport solution, elevating the system’s various components to Technology Readiness Level 6 (TRL6), moving towards the industrialization of a scalable electrified autonomous transport system for machines and vehicles.

Ericsson and Telia explored the 5G connectivity requirements of the digital site, with a specific focus on the autonomous transport service, and effectively showcased data flow differentiation.

Voysys investigated simulation environments for teleoperation and assessed the energy impact of seamless transitions from autonomous to teleoperated modes. Blekinge Tekniska Högskola (BTH) developed a modular digital twin for confined areas to evaluate the optimal setup of the autonomous fleet in a quarry, focusing on energy and productivity efficiency. BTH also collaborated with Volvo Construction Equipment to develop dynamic machine models for the larger electric hauler designed within the project. Additionally, Göteborg University examined requirements engineering for digital twins and AI in the context of confined area autonomous transport solutions.

2 SAMMANFATTNING PÅ SVENSKA

Gruv- och bergtäktssindustrin står inför hållbarhetsutmaningar som hög energiförbrukning, växthusgasutsläpp och dåliga arbetsförhållanden. En stor del av växthusgasutsläppen kommer från transport av utvunnet material med dieseldrivna tunga maskiner, vilka släpper ut CO_2, NO_x och partiklar som bidrar till luftföroreningar och klimatförändringar.

För att hantera dessa problem utforskar industrin flera alternativ:

- **Elektrifiering:** Elfordon (EV) producerar inga avgasutsläpp, vilket minskar koldioxidavtrycket. Begränsningar finns dock i batteriteknologi och laddinfrastruktur.
- **Vätgasbränsleceller (HFC):** HFC genererar elektricitet med vattenånga som biprodukt, erbjuder längre räckvidd och snabbare tankning än EV´s. Betydande framsteg i vätgasproduktion och tankinfrastruktur behövs.
- **Biobränslen:** Biobränslen, som biodiesel, kan användas i befintliga dieselmotorer med färre utsläpp. Deras hållbarhetsprofil beror på råvaror och produktionsmetoder.
- **Operativ effektivitet:** Optimering av rutter, minskning av tomgångstider och avancerad logistik kan också minska utsläppen.

Volvo Group är en nyckelaktör inom medelstora maskiner för bergtäktsverksamheter, för transport av laster på upp till ca 60 ton. Gruvsegmentet domineras dock av jättelika maskiner från tillverkare som Caterpillar och Komatsu, som har lastkapacitet upp till 300 ton. Batterielektriska fordon (BEV) använder litiumjonbatterier med energidensitet på 150 till 250 Wh/kg, ca 50 gånger lägre än dieselbränsle. En stor gruvlastbil kan bära 6000 liter diesel, vilket motsvarar 24 timmars drift, medan ett litiumjonbatteri med samma energiinnehåll skulle väga cirka 250 ton. Detta gör det utmanande att ersätta stora dieseldrivna maskiner med elektriska på en ett-till-ett-basis. Dieselfordon kan bära mer energi för samma vikt, vilket resulterar i längre räckvidd och högre lastkapacitet utan frekvent tankning eller laddning. Infrastruktur för tankning med diesel är mindre krävande än högeffektsladdinfrastruktur för BEV. Sammantaget gör detta att elektrifiering är beroende av nya sätt att designa och operera maskiner för att vara konkurrenskraftig.

I projektet Autonomous Electric Quarry (dnr 2015-003982), finansierat av Energimyndigheten, visade Volvo Construction Equipment och dess partners att det är möjligt att elektrifiera en bergtäkt och införa en elektrisk transportlösning som kombinerar manuella och autonoma maskiner och fordon. En flotta av autonoma HX02-maskiner, föregångare till TA15-maskinen, transporterade material som bearbetades av andra elektriska maskiner och elektrisk utrustning. Resultaten visade en potentiell minskning av CO_2-utsläpp med 98% och energikostnader med 70% för verksamheten i bergtäkten. Slutsatsen var att hela verksamheten måste elektrifieras och optimeras för att uppnå sådana höga minskningar i utsläpp och energi.

Genom detta projekt introducerade Volvo Group "Elephants to Ants"-filosofin, där en större dieseldriven maskin (elefant) ersätts av flera mindre maskiner (myror) för att utföra transporten. Till exempel kan en maskin med en lastkapacitet på 300 ton ersättas av flera mindre maskiner med lastkapaciteter på 60 ton, och en maskin som bär 80 ton kan ersättas av flera mindre maskiner med lastkapaciteter på 15 ton.

Autonomi bidrar till "Elephants to Ants"-filosofin, då det löser vissa utmaningar relaterade till förarbrist, personalkostnader och suboptimala arbetsförhållanden, inklusive säkerhetsrisker. Autonoma lösningar inom gruvindustrin har uppvisat betydande förbättringar i operativ effektivitet och bränsleförbrukning för traditionella dieseldrivna lastbilar. Att införa elfordon och maskiner i dessa autonoma lösningar kan ytterligare förbättra energieffektiviteten och minska växthusgasutsläppen. För att driva elektriska mobila maskiner och fordon effektivt krävs optimering av på alla nivåer; maskin, flotta, trafikhantering och hela gruvdriften. Omfattningen av effektivisering beror till stor del på den fysiska platsens förhållanden och sammanhang. Att utveckla en process som stöder elektrifiering och autonomi för maskiner och fordon i gruv- och bergtäktssammanhang kräver flera beroende teknologier, såsom positionering, mobil anslutning, infrastruktur och digitalisering. Dessutom är säkerhet, cybersäkerhet, efterlevnad av standarder och tillgänglighet kritiska dimensioner.

ASPECT-projektet har byggt vidare på resultaten från Autonomous Electric Quarry-projektet. Volvos autonoma elektriska transportlösning ligger i framkant av teknologisk innovation och kräver nära samarbete mellan fordons-, telekommunikations- och gruv- och bergtäktsindustrin för vidareutveckling till ett robust och skalbart industrialiserat system. Samarbeten med akademiska institutioner erbjuder nya insikter och lägger grunden för framtida framsteg. Genom sitt samarbete i ASPECT har ett konsortium bestående av Volvo Autonomous Solutions (V.A.S.), Volvo Construction Equipment (Volvo CE), Voysys, Telia, Ericsson, Blekinge Tekniska Högskola (BTH) och Göteborgs Universitet (GU) stärkt svensk expertis inom forskning, utveckling och innovation av uppkopplade, elektriska och autonoma transportsystem. Vi har genererat värdefulla data och kunskap som höjer nivån av innovation och internationell konkurrenskraft inom detta område. Dessutom har vi utökat vårt nätverk, etablerat nya partnerskap och skapat möjligheter för framtida samarbeten.

Projektmedlemmarna har träffats både digitalt och på plats i våra olika verksamheter, för att utbyta kunskap och erfarenheter och bidra till varandras arbetspaket och projektets resultat som helhet.

Ett axplock av projektets resultat inkluderar:

- Fortsatt utveckling av Volvos autonoma elektriska transportlösning för att uppnå Technology Readiness Level 6 (TRL6), vilket innebär ett stort steg mot industrialisering av ett skalbart elektrifierat autonomt transportsystem för maskiner och fordon. Vidareutveckling av ”site control & monitoring” systemet, för styrning och optimering av flottan i en gruva eller bergtäkt, inklusive en digital tvilling med fokus på översikt och kontroll av fordonsflottan och enskilda fordon/maskiner i realtid. (V.A.S.)
- Metod för att identifiera nyckelfaktorer i en gruva eller bergtäkt som påverkar hur den autonoma lösningen ska införas för en viss verksamhet utifrån dess fysiska och operativa förutsättningar. (V.A.S.)
- Konfigurering av 5G-mobilinfrastruktur och nätverk för att stödja simultana dataströmmar med olika krav på prioritet, latens och bandbredd. Dokumenterat arkitekturen för den digitala infrastrukturen. (Ericsson och Telia)
- Utvärdering av simuleringsmiljöer för teleoperering av maskiner samt bedömning av energipåverkan av sömlös övergång från autonom till teleopererad drift. (Voysys)
- Utveckling av en modulär digital tvilling för avgränsade områden, såsom en bergtäkt, för att identifiera den optimala sammansättningen av den autonoma flottan med fokus på energi- och produktivitetseffektivitet. (BTH)
- Utveckling av dynamiska maskinmodeller för den större elektriska maskin som designades inom projektet. Dessa modeller användes sedan i BTHs digital tvilling. (BTH, Volvo CE)
- Design av den nya elektriska maskinen utifrån de intressentbehov som identifierats med stöd av modeller och simulering av olika delar av maskinen. (Volvo CE)
- Utvärdering av laddteknologier och batterisystem för den nya maskinen. Utvärdering av laddstrategi för att optimera produktivitet, batterilivslängd och total ägandekostnad för elektriska maskiner inom den autonoma transportlösningen. (Volvo CE)

- Utveckling av digitala tvillingar och simuleringar för att verifiera och validera mjukvara inom det autonoma transportsystemet. (V.A.S.)
- Metod för kravhantering för digitala tvillingar och AI i sammanhanget av autonoma transportlösningar i avgränsade områden. (GU)

Resultaten har presenterats i seminarier på Volvos CampX Innovation Center i Lundby, Göteborg samt i en heldag med slutdemonstrationer och seminarier på AstaZero nära Borås. Deltagarna fick bl.a. se den större elektriska maskinen med hjälp av VR-glasögon samt testa simuleringsmodellerna som BTH och Voysys tagit fram. Vi fick en genomgång av Volvos kontrollrum på AstaZero och bevittna hur en lastbil körde en full autonom last-cykel på testbanan. Dagen avslutades med en livedemonstration från Ericsson och Telia där det mobila nätverket belastades med olika dataströmmar utan att påverka nödstoppets prioriterade signal.

En insikt under projektet har varit att Volvo inte har rådighet att förverkliga visionen om den kompletta elektrifierade och autonoma gruvan eller bergtäkten. Det är ett komplext nätverk av intressenter som styr olika delar av en gruva/bergtäkt, och det kan finnas olika förväntningar på den roll som Volvos transportlösning ska uppfylla. Projektet har därmed avgränsat sig till den energieffektiva autonoma elektriska transportlösningen och inte helelektrifiering av verksamheten i en gruva eller bergtäkt. Vi ser också att kunderna inte har fokus på detaljerad energioptimering, utan fokuserar på att ta första steget till elektrifiering av fordonsflottan på ett kostnadseffektivt sätt. Mognadsgraden är ännu för låg för att tala om energioptimering av en komplett verksamhet.

Det finns även utmaningar i termer av investeringsvilja och kostnader för en autonom och elektrisk lösning, som bland annat behöver mobila nätverk i miljöer som idag knappt är uppkopplade. En gruv- och bergtäktsmiljö är inte heller ”snäll” mot känslig elektronik och sensorer, vilket bidrar till praktiska utmaningar i form av robusthet och kostnader för reparation eller stilleståndstid.

Digitala tvillingar bidrar till en effektivare utveckling av mjukvara och maskiner och kan tillhandahålla stöd i säljprocessen och i driftsituationer. Mycket arbete återstår dock för att identifiera vilka digitala tvillingar som behövs för vilket ändamål, och vilka detaljer som ska återspeglas i varje tvilling för att uppnå dess syfte. Att försöka skapa en heltäckande digital tvilling av en verksamhet är komplext och svårt att realisera.

Och slutligen, säkerhet och ansvar för de risker som autonoma transportlösningar kan innebära har vuxit fram som en generell fråga de senaste åren, i samband med lansering av självkörande personbilar. Detta kan medföra ytterligare behov av tekniska lösningar, systematiska säkerhetsrutiner eller begränsningar i hur en gruva eller bergtäkt ska designas eller skötas i den dagliga verksamheten.

Vi sammanfattar med att ASPECT-projektet har bidragit till utvecklingen av en skalbar, energieffektiv och autonom transportlösning och främjande av nya transporttjänster och affärsmodeller inom svensk fordonsindustri. Genom tvärindustriellt samarbete och teknologisk innovation har projektet lagt grunden för framtida framsteg och samarbeten inom området för uppkopplade, elektriska och autonoma transportsystem.

3 BACKGROUND

Mining and quarry transport solutions and sustainability challenges

The mining and quarry industry faces sustainability challenges, including high energy demand, GHG emissions, and poor working conditions. A significant portion of GHG emissions comes from transporting extracted materials using diesel-powered heavy machinery, which releases CO_2, NO_x and particulate matter, contributing to air pollution and climate change.

To address these issues, the industry is exploring several alternatives:

1. **Electrification**: Electric vehicles (EVs) produce zero tailpipe emissions, reducing the carbon footprint. However, they are limited by battery technology and charging infrastructure.
2. **Hydrogen Fuel Cells (HFC)**: HFCs generate electricity with water vapor as a byproduct, offering longer ranges and faster refueling times. Significant advancements in hydrogen production and refueling infrastructure are needed.
3. **Biofuels**: Derived from renewable sources, biofuels can be used in existing diesel engines with fewer emissions. Their sustainability depends on various factors, including feedstock and production methods.
4. **Operational Efficiency**: Optimizing routes, reducing idle times, and implementing advanced logistics can also reduce emissions.

The Volvo Group is a key player in medium-sized machinery suitable for quarry operations, handling loads up to 60 tons. In contrast, the mining segment is dominated by giant haul trucks from manufacturers like Caterpillar and Komatsu, carrying payloads up to 300 tons.

Battery electric vehicles (BEVs) use lithium-ion batteries with energy densities ranging from 150 to 250 Wh/kg, significantly lower than diesel fuel. A large mining haul truck can carry 6000 liters of diesel, supporting 24 hours of operation, while a lithium-ion battery with the same energy content would weigh roughly 250 tons. This makes it challenging to replace large diesel-driven machines with electric ones on a one-to-one basis.

The difference in energy density between diesel and lithium-ion batteries has practical implications:

- **Range and Payload**: Diesel vehicles can carry more energy for the same weight, resulting in longer ranges and higher payload capacities without frequent refueling or recharging.
- **Infrastructure**: Diesel refueling infrastructure is less demanding compared to the high-power charging infrastructure needed for BEVs.

Figure 1 The autonomous electric HX02-machine in 2018 at the Skanska quarry Vikans Kross, Göteborg, Sweden.

In the project Autonomous Electric Quarry (dnr 2015-003982), funded by the Swedish Energy Agency, Volvo Construction Equipment and its partners showed that it is possible to electrify a quarry and introduce an electric transport solution that combined manual and autonomous machines and vehicles. A fleet of autonomous HX02-machines transported material which was processed by other electric machines and equipment (Figure 1). The results indicated a potential reduction in CO_2 emissions of 98% and in energy cost of 70% for the quarry operations. The main finding from the Autonomous Electric Quarry project was that the entire site must be electrified AND optimized to reach such a high reduction in emissions and energy.

Through this project, the Volvo Group introduced the Elephants to Ants philosophy, meaning that one manual, larger diesel-driven machine (Elephant) is replaced by multiple smaller electric and autonomous machines (Ants) to perform the transport. For example, a haul truck with a payload of 300 tons could be replaced by 6-10 smaller trucks with payloads of 60 tons and a haul truck carrying 80 tons could be replaced by 6-8 smaller haulers with payloads of 15 tons.

Autonomy is crucial for the Elephants to Ants approach, as it mitigates challenges related to driver shortages, personnel costs, and sub-optimal working conditions. Autonomous solutions have shown significant improvements in operational efficiency and fuel consumption in traditional diesel-based haul trucks. Introducing electric vehicles and machines into these autonomous solutions can further enhance efficiencies and reduce GHG emissions.

Implementing autonomous transport solutions in the mining and quarry industry presents new challenges and opportunities for the Swedish automotive industry, driving the need for cross-industry and academic collaborations. These collaborations will foster the growth of Swedish industries, create innovative technologies, and enhance Swedish exports of high-end products and services, particularly in machine learning, AI, electrification, and autonomous solutions integrated with the Internet of Things (IoT).

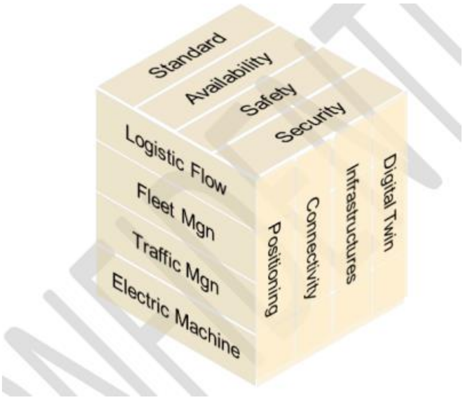


Figure 2 An electrified autonomous machine is part of a system of systems with different supporting processes and technologies.

The mining and quarry industry is well-suited for autonomous transport solutions due to its confined physical locations with restricted access, allowing for controlled interactions between humans, autonomous machines, and manually driven machines. This controlled environment eliminates certain complexities present on public roads. To run electric mobile machines and vehicles efficiently, optimization is needed in logistics flow, fleet management, traffic management, and machine efficiency. Developing a process that supports the electrification of machines and vehicles in mining and quarry contexts requires several interdependent technologies, such as positioning, connectivity, infrastructure, and digitalization. Additionally, safety, cybersecurity, adherence to standards, and availability are critical dimensions. This is illustrated in Figure 2.

By eliminating waste in various process steps, as illustrated in Figure 3, we can achieve energy optimization for the entire site. Introducing an autonomous transport solution in a confined area impacts most process steps, with initial steps focusing on machine and system setup and later steps emphasizing site design and system interactions. The extent of waste elimination depends on the site's conditions and context.

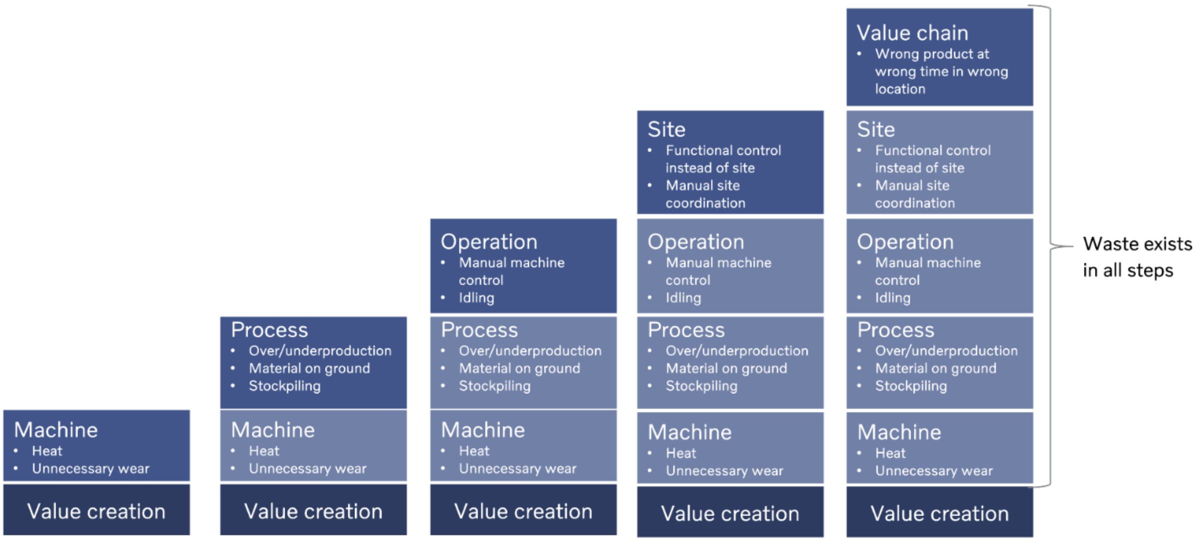


Figure 3 Waste in the process steps means that there are potential energy saving and productivity increases in a site.

Mobile connectivity, particularly 5G for industrial applications, is a crucial growth area for the Swedish economy. The telecom industry has determined that connectivity and communication are essential for enhancing energy efficiency and productivity in electrified and autonomous vehicles and machines. While societal focus has often been on high-volume, non-critical streaming services (e.g., YouTube, Play-services), autonomous transport solutions require handling simultaneous mixed signals with varying latency, bandwidth, and priority needs.

The efficient development and implementation of electric autonomous transport solutions and related services necessitate the use of models, simulations, and digital twins. These tools are vital at all stages, including software and hardware development, functionality verification and validation, and solution design for prospective quarries or mines.

The research profile MD3S – Model Driven Development and Decision Support (https://www.productdevelopment.se/model-driven-development-and-decision-support/) - at Blekinge Tekniska Högskola (BTH) has focused on the development of digital models and use of data in early design of complex systems, so called product service systems (PSS). This led to the development of decision models based on simulation and machine learning and to the creation of a physical design environment that integrates a cross-scientific simulation environment in a room of methods that could be used for simulation of an electric and autonomous site, such as a quarry.

Evolution of Volvo’s Autonomous Transport Solution

The Volvo Group continuously develops and adapts its products and services to comply with updated legislation, meet customer needs, and leverage new technologies. Traditionally, different teams within Volvo have focused on advanced engineering, research, and innovation across various product areas. For instance, advanced driver assistance systems (ADAS) have been developed since the 1970s to enhance safety and efficiency in personal and commercial vehicles and increase safety on the roads. Most people commonly associate autonomous vehicles with “self-driving” cars. However, ADAS is also relevant for commercial vehicles, where the techniques have been applied to improve, e.g., fuel efficiency and safety.

Figure 4 An electric autonomous hauler at Harsco Environmental in 2019.

The foundation for Volvo’s electric autonomous transport solution, the TARA concept, was established in the Autonomous Electric Quarry project and further developed with Harsco Environmental in Hofors in 2019 (Figure 4). Concurrently, Volvo Group Trucks Technology ran the Brönnöy Kalk project with autonomous diesel trucks (Figure 5).

Figure 5 Autonomous trucks meeting in the tunnel at Brönnöy Kalk, Norway.

Recognizing the need for a unified approach, Volvo Autonomous Solutions (V.A.S.) was created on January 1, 2020, merging advanced engineering teams from Trucks Technology and Construction Equipment. V.A.S. aims to develop autonomous fleets, both diesel-based and electric, advancing Volvo’s capabilities in autonomous transport solutions and new service-based business models.

A pilot implementation of the TARA transport solution began at a Swiss quarry in 2020, replacing the HX02 with the TA15 hauler. To scale and commercialize the autonomous transport solution, a shift from prototype-based development to a robust industrial product and service approach is required. This involves maturing the hardware, software, and interdependent technologies to ensure reliability, predictability, maintainability, and cost-efficiency.

To industrialize and raise the TRL levels of the autonomous transport system (ATS) components, V.A.S. merged and reworked existing solutions into a common technological platform, the Confined Area Autonomous Transport System (CAATS), suitable for various base vehicles and machines within the Volvo Group (Figure 6).

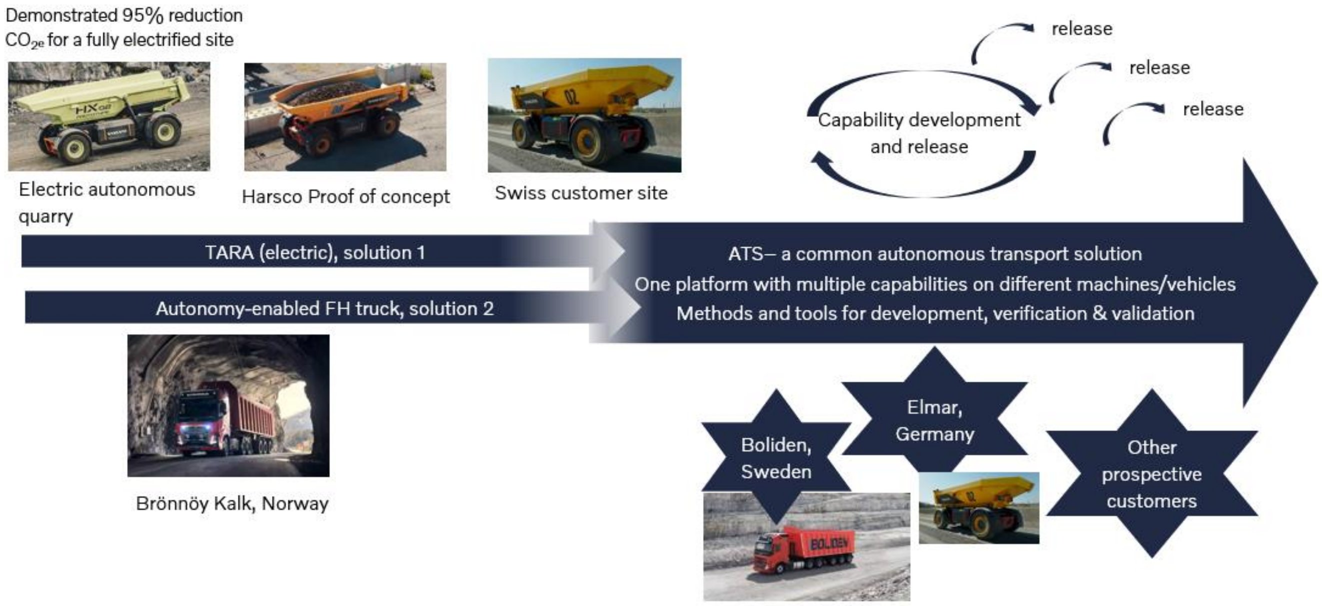


Figure 6 Evolution of Volvo's autonomous transport system.

4 PURPOSE, RESEARCH QUESTIONS AND METHOD

4.1 PURPOSE

The main purpose of the ASPECT project has been to contribute to a complete electric and autonomous transport solution that is energy optimized, scalable, sustainable and reliable. By running machines and vehicles as an integrated transport solution, the overall process can be optimized, creating value and minimizing waste in the total transport solution, not only in individual machines and vehicles. This has included the further development of the Volvo Group autonomous electric transport solution, taking the system's different components to TRL6, towards industrialization of a scalable electrified autonomous transport system of machines and vehicles.

Other purposes included:

- Enabling expansion into the mining transport segment for Swedish automotive industry, based on the Elephants to Ants philosophy, by designing the challenging sub systems of a new Volvo electric medium-sized hauler, the TAXX.
- Strengthening the Swedish capacity and competence within research, development, and innovation of connected, electric and autonomous transport systems as well as contribute to our international competitiveness.
- Contributing to industrialization of availability and standardization of 5G system infrastructure for electrified machines and vehicles.
- Generating data and knowledge to be used in future innovations and technology development.
- Increasing the cooperation between academia and industrial partners within the eco system of electrified and autonomous transport solutions through a cross-industry cooperation between automotive and telecommunications partners as well as academic partners within simulation and modelling. With active partnerships, we aim to uncover new business models and the roles of the different actors in the eco system – automotive manufacturers, charging systems, system suppliers, operation and support of the industrial site and its components.
- Enabling the shift from a product-focused business model to a transport solution service-based business model. This will lay the foundation for a future product life cycle that contributes to sustainability targets, circular business models and solutions that provide future benefits to society.

4.2 RESEARCH QUESTIONS

The project intended to answer, among others, the following research questions:

- How should a system be designed to be scalable and energy efficient, with electric machines and vehicles working in a common process?
- How should charging technology be designed for sites with large electric machines and vehicles?
- What services are needed for a fully electric facility? How should the site be set up and energy optimized, and how should the digital infrastructure for communication and information management be shaped to enable this?
- What requirements are there for scalable electric machines and infrastructure for energy- and productivity optimization of processes?
- How can an electric, energy efficient site be planned, optimized, and operated with the support of a digital twin where machines, systems and people provide input to cooperation?

- How should the method be formulated and what functional and non-functional requirements are there for a physical and digital infrastructure for a site of fully electric, connected and autonomous machines?
- Can teleoperation be used to increase productivity of electrified machines to increase their competitiveness vs diesel-fueled machines?

4.3 METHOD

The project was organized in different work packages (Figure 7) where each partner had ownership of one or more work packages while also contributing to other work packages.

Work package V1 (Volvo): Design of a new medium-large electric machine and its associated charging technologies and infrastructure. Volvo Construction Equipment (Volvo CE) managed this work package, in close cooperation with Volvo Autonomous Solutions (V.A.S.).

Work package V2 (Volvo): Development of the autonomous transport solution, with specific focus on an energy-efficient transport management for a fleet of electric and autonomous machines and vehicles. V.A.S. managed this work.

Work package H1 (Volvo): Project management and coordination of the ASPECT consortium.

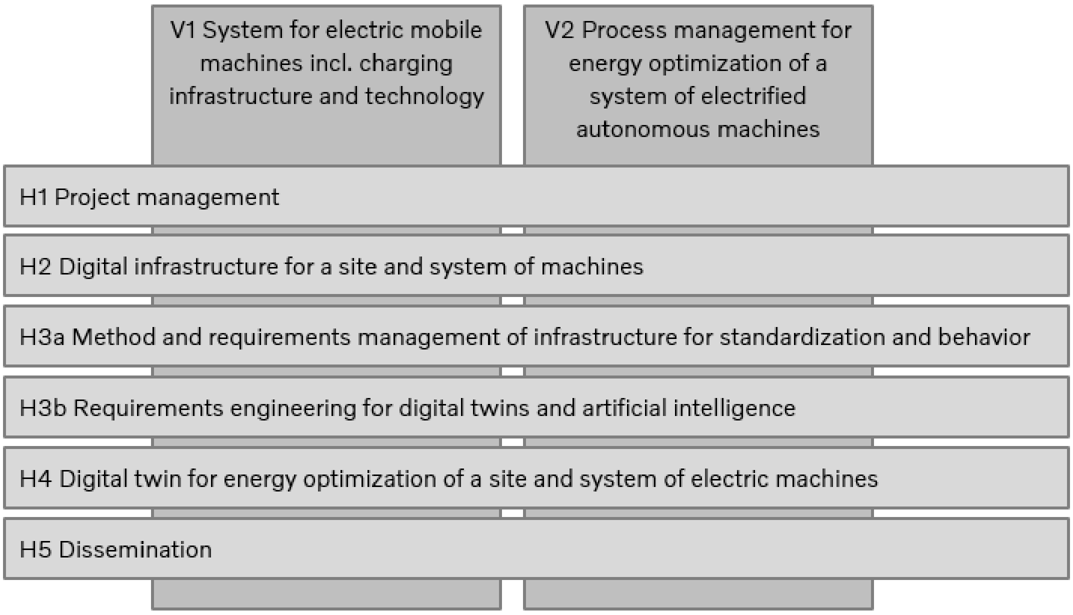


Figure 7 The project was organized according to work packages, managed by the different partners.

Work package H2 (Ericsson & Telia): Investigation and design of key characteristics of a 5G network required for an autonomous transport solution, to secure the architecture for the digital infrastructure and requirements on information flows used within a site.

Work package H3a (Volvo): Requirements management for site infrastructure and implementation.

Work package H3b (GU): Requirements engineering for digital twins and AI and development of a method for requirements elicitation for digital twins.

Work package H4 (BTH): Development of a modular digital twin to represent an electric site and provide input to an optimal setup of the site from an energy efficiency and productivity perspective. BTH also worked closely with Volvo CE to define relevant machine models for the TAXX digital twin.

Work package H5 (Volvo): Dissemination and communication. All project partners performed their own dissemination activities and participated in the centrally organized activities.

Each work package leader defined their own working method and set up sub-groups with relevant resources from the project consortium and their own organization's resources. The project also had multiple knowledge-sharing sessions and workshops, to enable the cross-industry-academia competence development in electric and autonomous vehicles and to fuel the work done within each work package.

The ASPECT partners incorporated experience and input from multiple stakeholders within the industries global mining & quarry, automotive and telecommunication. We interacted with ongoing feasibility studies, pre-studies and projects to take part of customer-specific and technical information, as input to our work packages. For example, we made use of hands-on learnings from on-going pilot projects for autonomous transport solutions within V.A.S. The project did not center around a specific physical quarry, like in the Autonomous Electric Quarry project. Instead, we defined a "typical confined area" which could be either an open pit mine or a quarry. By identifying the necessary operational components in a quarry, the project partners were able to work towards the same vision of the connected, electric and autonomous transport solution and confined area when producing our results. Figure 8 shows a schematic autonomous and electric quarry and the different infrastructure components that could be relevant to the autonomous transport solution and regular site operations.

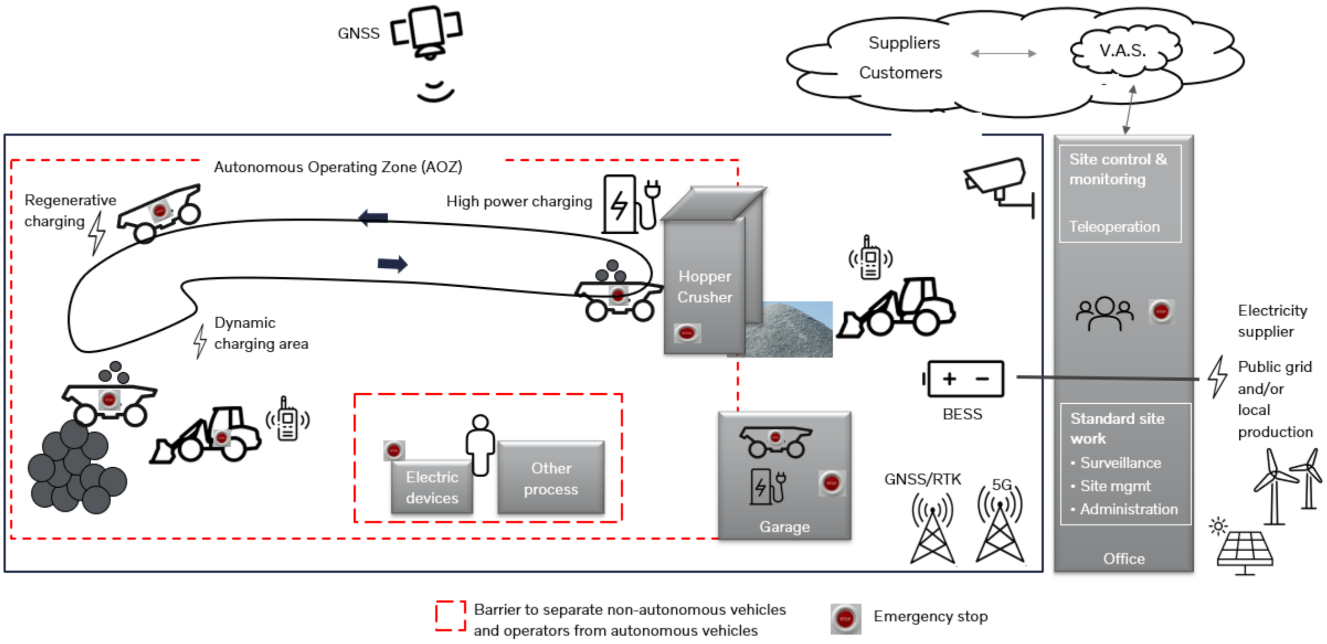


Figure 8 Schematic of key components in a site running an autonomous transport solution.

These could include:

- Office area with Control Tower (site management system, teleoperation equipment, surveillance)
- Autonomous Operating Zone (AOZ), which in the future could be divided into several Autonomous Operating Areas with geofencing, separate emergency stops, etc.
- Autonomous transport solution(s) consisting of
    - Several autonomous machines or vehicles (could also be teleoperated)
    - Emergency stop and other security and safety measures (gates, light barriers, physical barriers)

    - Environmental sensors
    - Charging infrastructure
    - Teleoperated equipment
    - Manually operated equipment, e.g. loading equipment (wheel loaders, excavators)
- Other electrical production units
- Video surveillance equipment
- Personnel with communication devices (walkie talkie, handheld devices with HMI)
- Other connected devices – safety vests, traffic control equipment
- Local network, with connection to Internet
- GNSS/RTK solution for navigation
- Battery storage of electricity (from main grid or local production) to enable required or higher productivity or to balance energy requirements (peak power)

The confined area and mining and quarry operations are described more in Chapter 6.5, as part of work package H3a.

5 OBJECTIVES

The main objective for ASPECT was to develop conditions for an energy efficient system of electric machines, including

- Process management for energy optimization of a system of electrified autonomous machines
- A system of electric and autonomous mobile machines, including a new larger electrified and autonomy-enabled hauler and its charging technology and infrastructure
- 5G connectivity for the connected system of machines and equipment
- A digital twin for the transport solution in a confined area (open pit mine or quarry)
- Method and requirements management for the site, infrastructure and transport solution

The project objectives are summarized in Table 1, along with an estimated completion rate and explanatory comments for deviations.

Table 1 Overview of the main project objectives and their estimated completion rate.

Objective	Estimated completion	Comment
Design and/or select charging technology, dynamic charging and infrastructure for electric connected and autonomous machines in a confined area, applied to the TAXX.	80%	We know what is needed and have identified options. However, certain choices cannot be made until later in the prototype/build phase or as defined by local site requirements,
Design process management for different applications of the transport solution, focusing on electrification and energy optimization in confined areas. Develop the prerequisites for an energy effective process of electrified machines and vehicles.	100%	
Develop a reference architecture for digital infrastructure and information flows. Investigate the conditions for a 5G-connected system of site, machines, and vehicles.	100%	
Define a method to identify functional and non-functional requirements that must be met by a confined area to enable electrified and energy-optimized transport solutions.	100%	
Design virtual models suitable to describe electrical machines, vehicles, and the solution environment to enable detailed energy optimizations.	70%	A modular digital twin for a site has been developed and demonstrated by BTH. Virtual models have been created for the TA15, FH and the TAXX. Models for the TA15 and FH are used in the internal V.A.S. simulation environment and for TAXX in the BTH digital twin. Models for TAXX cannot be validated until the physical counterpart exists. The use of virtual models to verify the solution in a simulated environment, saves energy and emissions in the development of the autonomous transport solution and allows for optimized site deployment.

Increase the research and innovation capacity and competence within connected electrified machines in Sweden. Contribute to our international competitiveness and create job opportunities.	100%	
Generate data and knowledge that can be used in future development projects.	100%	
Contribute to cooperation between academia and industrial partners to enable a Swedish eco-system for electrification and connectivity of machines.	100%	
Lay the foundation for a future product life cycle, contributing to sustainability goals with circular business models and solutions for future societal benefit.	100%	

Some changes were made to the scope during the project. One initial objective for the ASPECT project was the energy optimization of an electric and autonomous site. Based on the results from Volvo's projects Autonomous Electric Quarry and Harsco, it was believed that the basic autonomous transport system was stable. Going forward, focus should be on scaling and industrializing the system, considering process and energy management for the autonomous fleet and entire electric site. During the project, it has become clear that the autonomous transport system and the environment in which it operates is more complex and challenging than initially anticipated. Additional knowledge of the mining and quarry industry has been gained over the past years through visits and meetings with other prospective customers as well as pilot projects. We have therefore had to focus more on the autonomous electric transport solution within a site and less on a fully electrified site. The fully electrified site is in the control of the site owner. The vision of a connected electric site with real-time optimization of energy usage and the use of digital twins to improve the energy efficiency of a site in real-time will not be relevant in the near future.

Due to commercial and confidentiality reasons, the project did not identify a future customer in which to deploy the autonomous transport solution as a follow-up project after ASPECT. Volvo Autonomous Solutions will manage this as part of ordinary business practices.

6 RESULTS AND DELIVERABLES

6.1 OVERVIEW OF RESULTS

Through ASPECT, we have contributed to the development of a Swedish autonomous transport solution, paving the way for a next generation of services and solutions within the automotive industry and within new industry segments. We have had a successful collaboration across the telecommunications and automotive industries, as well as with universities and smaller tech companies. Employees and students have been exposed to interesting technical and commercial questions, which they will bring into their future work and careers, contributing further to the Swedish technological and innovative landscape.

The project has contributed to the design and development of an energy-efficient scalable system of autonomous electrified machines and vehicles, including charging technology, charging infrastructure and models for a new TAXX machine. We have created digital twins within different parts of the solution and identified key requirements on the 5G-mobile network. We have raised the TRL levels on critical components and on the whole solution.

We have contributed to the development of the new Confined Area Autonomous Transport System (CAATS), which has been validated in the V.A.S. Generic Test Site at AstaZero on both the electric TA15 and diesel-based FH trucks. By establishing a “code factory” with a simulation and coverage-driven test approach as well as a generic test site at AstaZero, Volvo is now positioned for a rapid development and scaling of the ATS in terms of vehicle/machine control, process and fleet management and validation of infrastructure and safety measures. The autonomous transport solution is currently being implemented at a Swedish mining customer with a diesel-based fleet as a first step, soon to be followed by implementation at two customer sites in Germany with the smaller electric TA15. The “cloud services” developed in the project have been renamed Site Control & Monitoring, a sub-system to manage the fleet, production and traffic within a site. Energy optimization at a site level has been determined to be mainly an output of the initial site design, as well as the sum of interaction of all underlying components in the autonomous transport solution.

Energy efficiency in the ATS is achieved by

1. Ensuring that each vehicle/machine performs optimally when executing its tasks, e.g. by efficient driving in varying site conditions.
2. Traffic control of the entire fleet to reduce idling and other productivity losses.
3. A charging strategy at vehicle/machine level and fleet level to optimize productivity on site together with battery life and total cost of ownership.
4. Using simulations to verify the system functions before they are deployed to physical test or customer sites.
5. Designing each site to minimize the number of machines needed in the fleet, optimize logistic flows and productivity and minimize interruptions or down-time.

Teleoperation of vehicles/machines is an area of interest not only for an autonomous fleet but also for other equipment used in confined area or in other applications. Within ASPECT, we have taken the first steps to investigate a seamless transition between autonomous and teleoperated mode, including the setup of a customized simulation model, to be used for further development of teleoperation capabilities.

A new medium-sized electric hauler, the TAXX, has been designed by Volvo CE. A key element was to identify appropriate charging solutions and charging infrastructure. Instead of designing these from scratch, Volvo decided to go with standardized market components and use different combinations to suit the conditions of each site. However, the market is still evolving in this area so the final solution may look different and depend on new standards and development of charging technologies.

Researchers at BTH created a modular method to define a digital twin of a site and evaluate the optimal configuration in terms of vehicles/machines from an energy and productivity perspective. The method was demonstrated on a digital twin of the Volvo Eskilstuna Customer Center test site, with machine models of the TAXX and TA15. The machine models for TAXX were developed by BTH together with the designers from Volvo CE. The results produced by BTH are of great importance to V.A.S., as input to future simulation software to support the autonomous site design, implementation and operation.

In parallel, V.A.S. has set up an in-house simulation environment to perform hardware-in-the-loop and software-in-the-loop testing using digital twins of sites and vehicles/machines. This allows for shorter lead-times in software development and verification as well as a more efficient use of physical resources – machines, humans and test sites.

Ericsson and Telia worked with V.A.S. to investigate the requirements for digital infrastructure in terms of connectivity and needed properties of a 5G network to support an autonomous transport solution. They demonstrated that it is possible to prioritize different signals in the network to ensure that critical signals always have priority. This is an important requirement for the emergency stop function and other critical signals.

The V.A.S. team has defined a method to identify key requirements for site and infrastructure design, in the form of questions to be discussed with prospective customers during the feasibility and prestudy phases. In parallel, Göteborg University has identified a method to elicit requirements for digital twins and investigated the impact of AI on requirements engineering.

Table 2 provides a summary of the Technology Readiness Level (TRL) at project start and at project completion. The TRL definition can be found here.

Table 2 Evolution of TRL levels during the project.

WP	**Technical area**	**TRL at start**	**TRL goal**	**Actual TRL**	**Comment**
H2	Digital infrastructure for a site and system of machines and vehicles	3	6	8 7	Private 5G is commercially available and configurable for the ATS's needs The digital infrastructure has been set up and validated at AstaZero, under production-like circumstances
H3	Method and requirements mgmt. for infrastructure and standardization	2	4	6	Applied to real customer cases during pre-studies for quarry and mining.
H4	Digital twin for energy optimization of a site and system electrical machines	2	5	5 7	Partial DT and models for a site Simulation env for development and verification of the ATS software and autonomous driving hardware components

V1	System for electrical mobile machines: TAXX machine	4	6	6 2	System in general TAXX
V1	System for electrical mobile machines: Battery technology	3	6	8	Volvo Group electromobility used for trucks and other vehicles commercially
V1	System for electrical mobile machines: Charging technology	2	6	7 2 – 7	Pantograph for TA15 verified in operation at Swiss customer. Components available at high TRL but integration of components for TAXX not yet possible
V1	System for electrical mobile machines: Charging infrastructure	2	6	6	Commercially available; integration and validation of entire system required
V2	Fleet management for energy optimization of a system of electrified machines	2	6	7 6	Previous generation ATS piloted in Switzerland CAATS verified at AstaZero.

In the following sections, we describe the results of each work package. We present V2 before V1 to create a better flow, starting with an overview of the autonomous transport solution and the fleet management, before going deeper into the TAXX, connectivity, digital twins and requirements management in the subsequent chapters.

6.2 V2 - PROCESS MANAGEMENT OF A SYSTEM AND SITE OF MACHINES AND VEHICLES

6.2.1 Objectives

The objective of work package V2 was to build a cloud solution for a system of electrical machines and vehicles. We would design how process management will be executed, shaped and integrated to contribute to an energy efficient and productive transport process (including automated and teleoperated machines).

Work package V2 also took charge of some of the deliverables from work package V1 (Chapter 6.3). The key objectives are summarized in Table 3 and the key deliverables in Table 4.

Table 3 Key objectives and status.

Key objective	**Status**
Build a cloud solution for a system of electrical machines and vehicles	Completed; validated in the new Generic Test Site at Asta Zero. Renamed Site Control & Monitoring, this “orchestra conductor” manages the autonomous fleet for both diesel-based and electrical machines and vehicles.
Design how process management will be executed, shaped and integrated to contribute to an energy efficient and productive transport process (including automated and teleoperated machines).	Completed. Design of process management for the fleet and support systems within a confined area has been finalized. Focus within teleoperation has primarily been on creating a digital simulation environment, to be used for future development.

Develop the interface through which the machines/vehicles communicate with the digital infrastructure.	Completed. Developed a control module to interface the machine/vehicle and the Site Control & Monitoring system.

Table 4 Key deliverables and their status.

Deliverable	**Status**
Technical solution for cloud; technical solution for different subsystems and energy optimization.	Completed. Site Control & Monitoring sub-system.
Technical solution for remote control of electric autonomous machines and vehicles in a virtual site.	Partly completed. Simulation environment to demonstrate seamless transition from autonomous to teleoperation was built and demonstrated. Teleoperation is necessary in the long term but has not been prioritized in the short term.
Technical solutions, in terms of interface and functions, to create conditions for energy efficient use of machines in operation in a system of machines	Completed (from V1). A control module is introduced into each machine, to act as an interface between the machine, the driver and Site Control & Monitoring. This is part of the so called autonomous driving (AD) kit that converts a vehicle/machine into an autonomy-enabled V/M.
Method for requirements arbitration within a system of machines to adapt to different sites and applications.	Completed (moved from V1). Managed in SC&M and through the site design process and requirements management method described in work package H3a.

6.2.2 Overview of the confined area autonomous transport system

The autonomous solution defined in the Autonomous Electric Quarry project was a prototype solution developed as a proof-of-concept. To raise it from TRL 2 to TRL 6 or higher required an overhaul of the different components of the system. To industrialize and scale, the underlying components must be available, robust and work together in complex, physical situations. During the work to merge the different solutions available within the Volvo Group, an overarching system architecture has been defined to describe the confined area autonomous transport solution (CAATS, or ATS). The system consists of five key sub-systems containing different components (Figure 9):

- Site Control & Monitoring – the central functionality that manages and oversees the fleet and relevant on-site support and safety systems
- Driver (on each vehicle/machine) – executes orders from Site Control & Monitoring and plans the motion of its vehicle/machine
- Autonomy-enabled machine or vehicle – base vehicle/machine + autonomous driving components
- Safety systems – emergency stop, barriers, safety procedures
- Infrastructure & support systems - mobile connectivity, GNSS, loading equipment, charging stations

Work package V2 focused on the Site Control and Monitoring system and process management of the entire system and the energy-optimized site, which touches upon all sub-systems in one way or another.

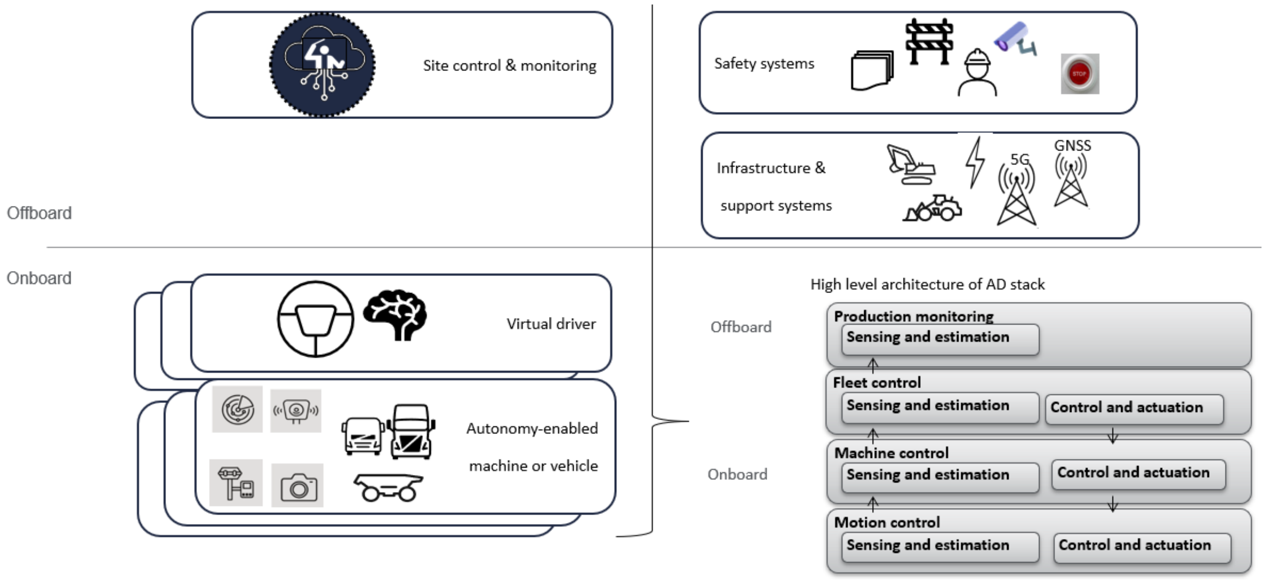


Figure 9 The CAATS architecture. Onboard= on the vehicle/machine. Offboard = not on the vehicle/machine.

The autonomy-enabled vehicle/machine consists of a "base vehicle/machine" and an autonomous driving (AD) kit. The AD kit contains, for example, perception and localization components like lidar, radar, GNSS, cameras and control modules. The AD kit has been standardized to work with different base vehicles/machines, but individual components can differ in number and placement depending on the type and size of the vehicle/machine. For example, a larger truck or hauler may need more lidars to "see" than a smaller hauler.

The sub-systems and components interact in real-time to execute the transport missions, as defined by the site operator in the Site Control & Monitoring system. Figure 10 illustrates one or more autonomy-enabled vehicles/machines with Site Control & Monitoring as the orchestra conductor telling the fleet what to do and in what order to do it.

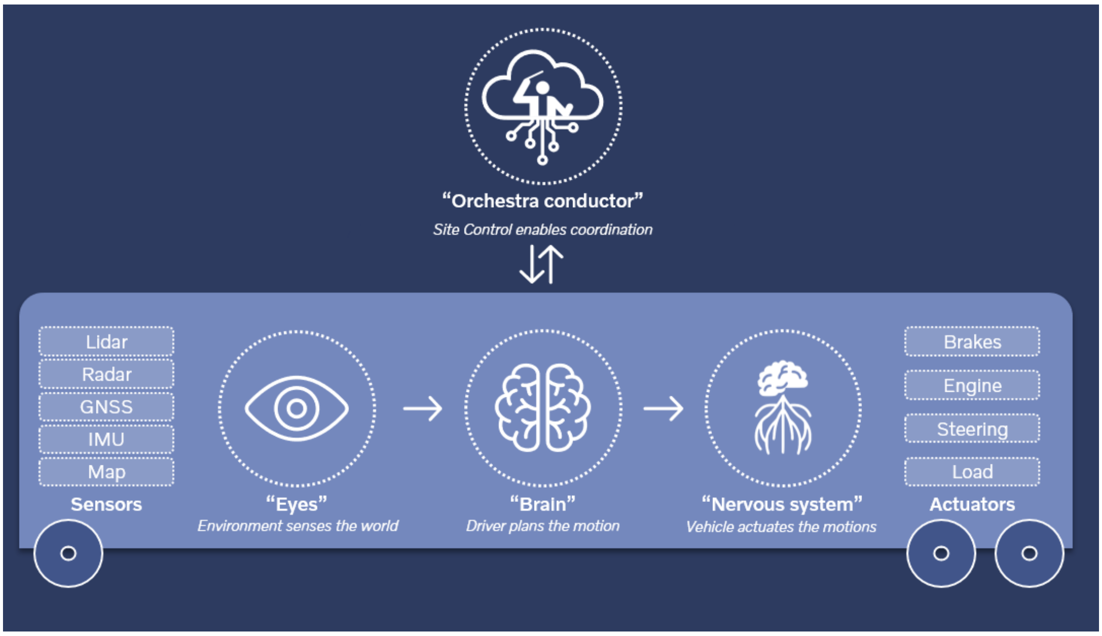


Figure 10 Illustration of the ATS with the Site Control & Monitoring sub-system as the orchestra conductor.

Interoperability in autonomous transport systems within mining and quarries is an evolving area with significant potential benefits for the mining industry. While the current status is characterized by proprietary systems developed by original equipment manufacturers (OEMs) like Komatsu and Volvo, and limited interoperability, mining industry initiatives and collaborative efforts are paving the way for more open and interoperable solutions. The Global Mining Guidelines Group (www.gmggroup.org) is a collaboration forum for the mining industry, focusing on autonomous mining, data & interoperability, the electric mine, and many other innovative topics. It became a separate legal entity in November 2021, shortly after the start of the ASPECT project.

Overcoming technical challenges, standardization issues, and security concerns will be essential to achieving seamless interoperability. In the longer term, the Volvo autonomy-enabled machine and driver must be able to integrate with a non-Volvo fleet management system and other machines, or the Volvo Site Control & Monitoring software needs to integrate with fleet management systems (FMS) or mining operating systems (MOS). The requirements for interoperability are still at an early stage and need to mature before they can be incorporated into the Volvo ATS, or autonomous haulage system (AHS) as it is called in Figure 11.

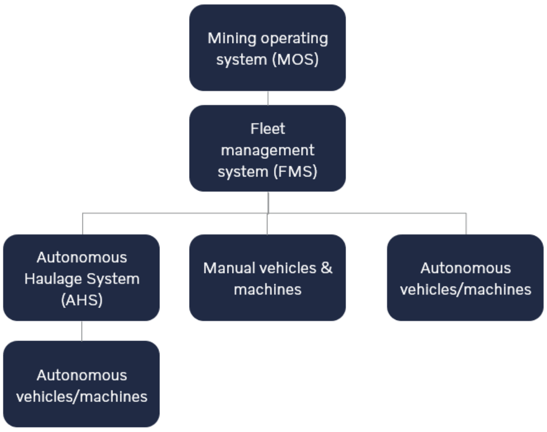


Figure 11 Illustration of the mining industry's vision of the fully interoperable mining site, with different brands of vehicles/machines.

6.2.3 Site Control & Monitoring (formerly called "Cloud services")

The sub-system Site Control & monitoring (SC&M) is the orchestra conductor that oversees and manages the entire autonomous transport system deployed in a site. The SC&M can be deployed on a local site server or in a Cloud-based service, like Amazon Web Services or Microsoft Azure. From a scaling and industrialization perspective, local installations are more cost effective until the volume of customers and sites tips the scale in favor of a Cloud solution. The system is designed to work in both settings.

A schematic of the SC&M sub-system is shown in Figure 12. Its three key functions are to manage the fleet, manage production and coordinate traffic. SC&M has been reworked since Autonomous Electric Quarry, both in terms of the underlying code and architecture and in the human-machine-interface. (HMI). One focus has been on simplifying the interface for the site operator, the other on merging the needs of the various customer applications for the autonomous transport solution and ensuring that the underlying code base is scalable and meets the long-term needs of the stakeholders. Additional work has been done to align with relevant standards, such as Earth-moving machinery and mining – Autonomous and semi-autonomous machine system safety (ISO 17757:2019). Vehicles (such as trucks) and machines (such as haulers) are often subject to different legislations and standards even though their application might be the same in a mine or quarry. We therefore write machine/vehicle or V/M to remind the reader that the autonomous transport solution needs to manage both types of load-carriers.

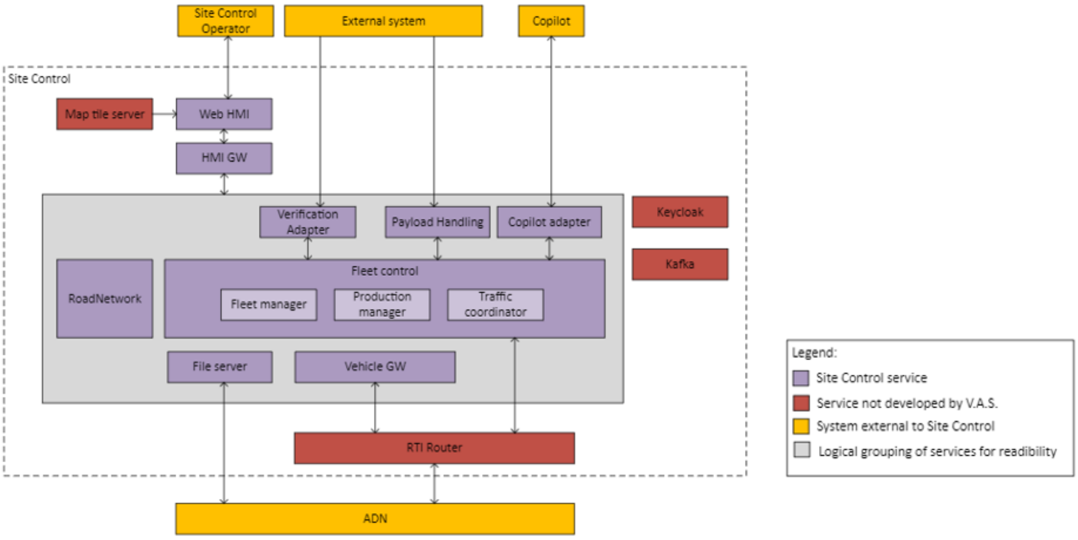
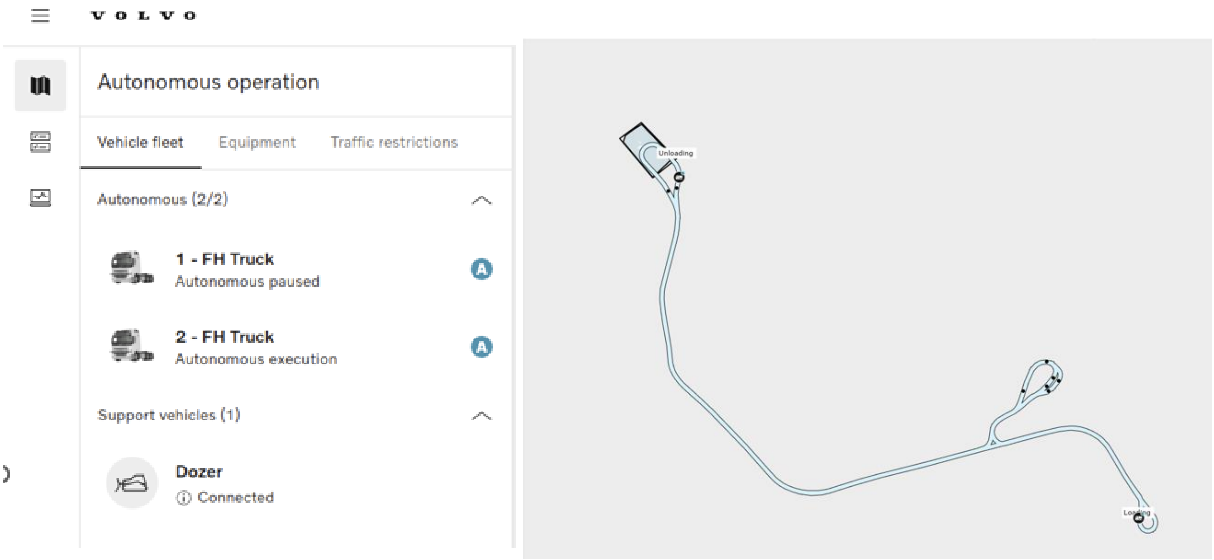


Figure 12 Overview of the Site Control & Monitoring sub-system and its interfaces.

The SC&M sub-system contains a digital twin of the site - the recorded maps of the site (GPS coordinates of the haul routes), pre-defined loading and unloading areas, intersections, location of chargers and information about each vehicle/machine. Status for each vehicle/machine (V/M) is continuously transmitted through the site's 5G network to SC&M, so that the site operator can monitor progress in real time through the system's web interface (Figure 13).

The site operator plans the day's production and defines the active loading and unloading areas through the web interface. S/he activates the autonomous V/M that are to be used for production, and, after selecting the relevant planning mission for execution, activates the fleet. The autonomous V/M then start executing each transport mission that they are given by the SC&M, based on segments in the map. Each V/M gets an instruction where to go next, e.g. to drive to the next intersection. It is provided information such as route, trajectory (coordinates), road curvature, maximum allowed speed and whether to navigate on GNSS or Lidar. SC&M has the overall status and location of all V/M in the fleet (Figure 13 and Figure 14) and can thus decide which vehicle/machine has priority in an intersection, or whether a V/M should charge or continue without charging. Each instruction is pushed to the V/M, ensuring a smooth flow of traffic and the ability to replan the traffic if needed.



Autonomous (2/2)

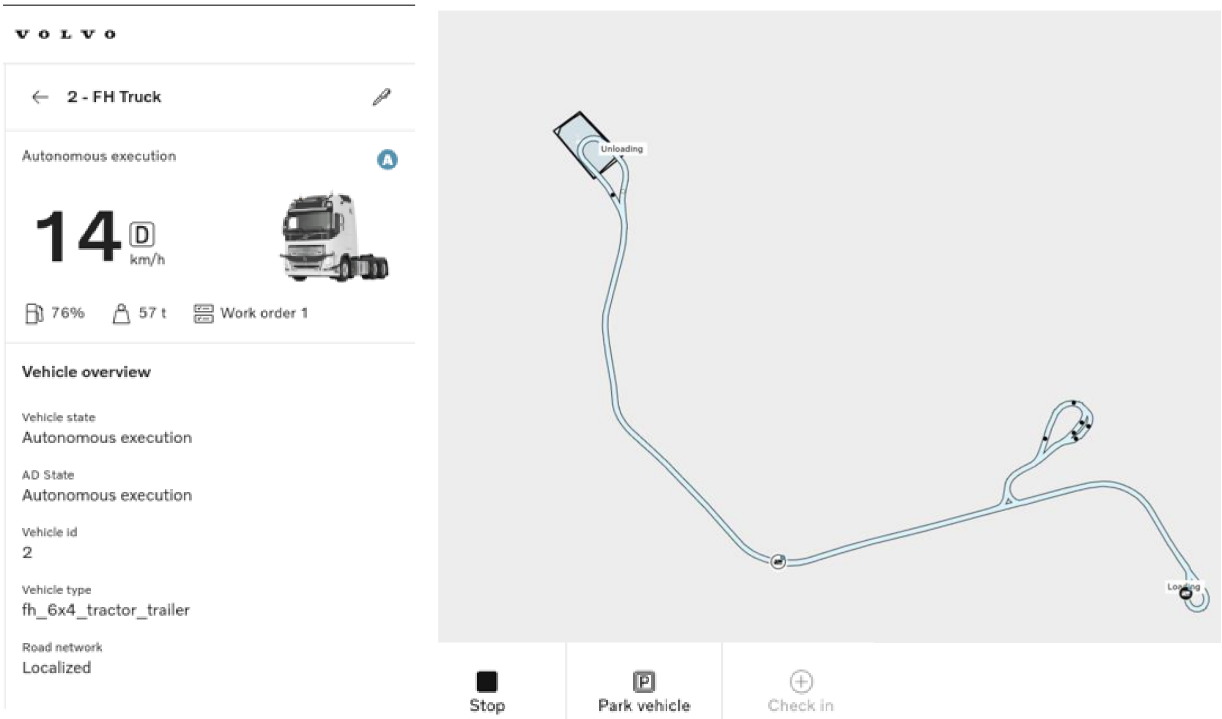
1 - FH Truck
Autonomous paused

2 - FH Truck
Autonomous execution

Support vehicles (1)

Dozer
Connected

Figure 13 Site map in SC&M with two autonomous vehicles, a loading spot, an unloading spot and a primary haul route. In this scenario, a bulldozer is used to load the autonomous vehicles.



Autonomous execution

14 D km/h

76%   57 t   Work order 1

Vehicle overview

Vehicle state
Autonomous execution

AD State
Autonomous execution

Vehicle id
2

Vehicle type
fh_6x4_tractor_trailer

Road network
Localized

Figure 14 Detailed information for vehicle #2.

For electric vehicles, the state of charge will be displayed instead of fuel level. Some of the architectural components in the sub-systems Safety System and Infrastructure & Support System shown in Figure 9 have an indirect impact on Site Control & Monitoring, whereas others are directly linked. For example, 5G connectivity is a requirement for communication between V/M in the fleet and Site Control & Monitoring. SC&M does not monitor or manage the 5G connectivity, but if a V/M in the fleet loses connectivity with SC&M it will continue to its destination and then stop to wait for the next instruction. However, if the heartbeat signal for the emergency stop is lost, the V/M is stopped, in accordance with relevant ISO standards.

The SC&M sub-system integrates to the loading tool (excavator, wheel loader, etc.) through the Co-pilot interface. Within the loading tool, the operator has a tablet with which to interact with SC&M, e.g. to indicate the exact spot for loading or to signal when s/he is ready to receive the next autonomous vehicle/machine. SC&M then dynamically plans the appropriate route and relays this to the V/M.

Figure 15 illustrates the different steps in the Load Cycle, and factors that impact the efficiency of the steps in terms of time (productivity) and/or energy.

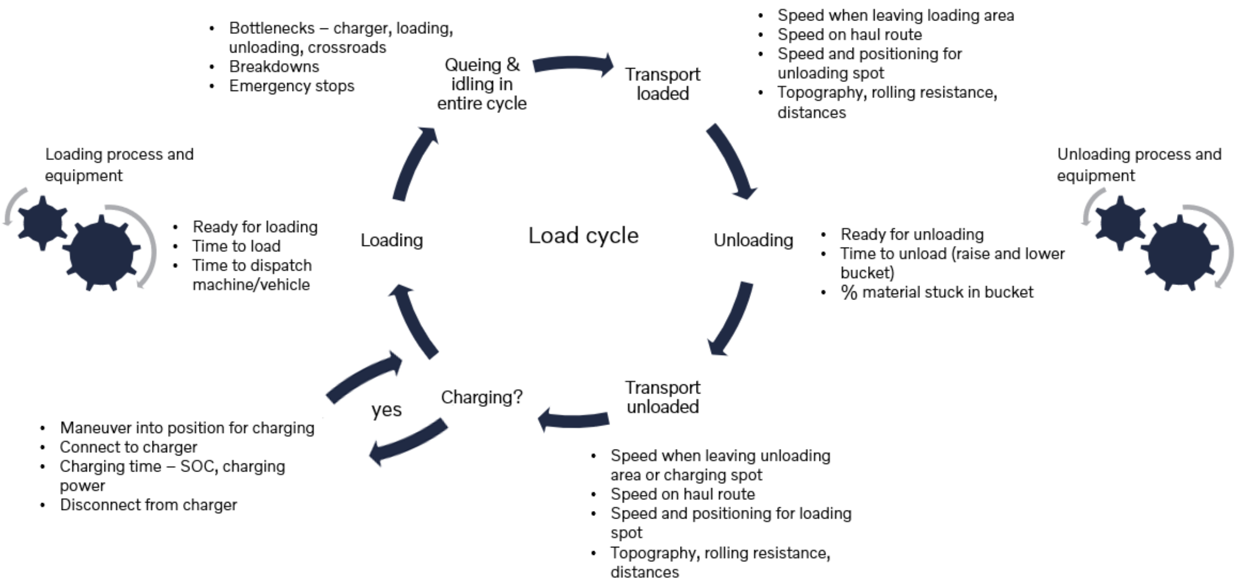


Figure 15 Illustration of the Load Cycle and factors that impact energy efficiency and productivity.

When the transport mission is initiated, queues initially form e.g. for loading and charging, but as the day progresses, the traffic flow evens out, and the fleet performs optimally. The bottlenecks are mainly found in loading, charging and unloading since these are sub-processes that contain their own delays and inefficiencies. For example, loading by excavator or wheel loader is not instantaneous but requires one or more scoops, with time to maneuver and load in-between scoops. Unloading to a crusher requires that the crusher speed and material handling out of the crusher match the flow of material into the crusher from the autonomous vehicles. Table 5 describes how productivity and energy efficiency are impacted by each step. These are factors that will differ from site to site and from one load cycle to the next. They can be addressed during site design before implementation of the ATS, but ultimately lie outside of the control of SC&M during operation. The SC&M sub-system can receive and send signals to and from the loading and unloading systems to monitor status and guide the autonomous fleet, but it cannot impact their efficiency.

Table 5 Impact on productivity and energy efficiency by different steps in the load cycle in Figure 15.

Step/activity in the load cycle	**Impact on time, productivity or energy efficiency**
Leaving or entering loading/unloading area	• Lower speed to increase precision, depending on unloading/loading method. • In CA2, there can be interaction with a manual vehicle which requires restriction of speed.

	• Lower speed and more maneuvering → longer load cycle and lower productivity.
Travel on haul route	• Drive at the maximum speed possible, defined by the maximum speed allowed by SC&M, road conditions and topography and the efficiency of signals and responses at the driver- and vehicle/machine-level.
Ready for unloading	• Equipment/method for unloading must be ready. E.g. if the crusher is full, unloading must wait until signal is green.
Time to unload (raise and lower bucket)	• Physical limitation of the bucket and hydraulics – time to raise and lower the bucket. • If manual unloading by some unloading equipment, time to empty the bucket.
% material stuck in bucket	• Waste is possible if the bucket cannot be fully emptied, e.g. due to sticky material like wet limestone. • This could be reduced by lining of the bucket.
Maneuver into position for charging	• The method for automatic charging and the precision required for positioning has an impact on time.
Connect to charger	• The time to connect the charger and the vehicle/machine depends on the charging equipment and how robust the connection is. If connectors are covered in dirt or corroded, this will have a negative impact on the connection.
Charging time – SOC, charging power	• Time to charge depends on current state-of-charge of the vehicle/machine and the charging power provided. • The charging strategy has an impact on time to charge, for each individual charging event and for charging over the entire transport mission and production cycle.
Disconnect from charger	• Successful disconnection and signaling that the vehicle/machine can leave the charging area is required.
Bottlenecks – charger, loading, unloading, crossroads	• Bottlenecks in terms of queueing to the charger, loading spot or unloading spot can impact productivity. • If queueing at the loading spot depends on the speed and size of the loading equipment, then this might need changing. • If queuing is due to inefficient charging or lack of chargers, then the charging capacity needs to be increased. • Crossroads and intersections may introduce delays, depending on traffic intensity. • The initial site design can consider these things, but only when the autonomous transport solution is deployed on site will it be possible to do the final optimization of the solution. Much work can be done in the design phase, with manual calculations or by using models and simulations as described in Chapter 6.6.4.
Breakdowns	• Breakdowns of equipment, whether in the autonomous fleet or in supporting equipment, will negatively impact productivity. This can be mitigated by having one or more spare vehicles/machines on site, but this has a negative impact on the total cost of ownership and ties up capital and machines. Having spare parts on site and the ability to repair machines and vehicles is an advantage, but special competence could be required which may not be available on-site. • The robustness and reliability of the vehicles/machines are therefore key factors in terms of productivity, profitability and CO_2 emissions.
Emergency stops	• Emergency stops have a significant negative impact on system performance and productivity.

	• The site and processes must be designed to avoid situations that trigger unnecessary emergency stops, e.g. by ensuring that no one can enter the AOZ when the autonomous fleet is in operation.

As the ATS matures and we move to higher Confined Area levels, the speed at which interaction with loading and unloading tools can occur should increase as safety measures become more integrated into the systems and rely less on protective measures and safety procedures.

The charging strategy, i.e. how and when to charge each machine and what SOC-window to apply, has a large impact on productivity and on the total cost of ownership. How the batteries are used and charged on a site impacts their state-of-health and determines how often they need to be replaced during the lifespan of the machine. The Site Control & Monitoring sub-system is the master, controlling when a machine charges. The SOC window is set both on machine level and by the SC&M system. For more information about batteries and state-of-charge, see Chapter 6.3.14.

6.2.4 Teleoperation use cases

Teleoperation is where humans steer a machine or vehicle from a distance using video and other data feeds. There are different applications or use cases where teleoperation might be relevant, and they each impose different requirements on latency in the mobile connectivity and on the safety case.

Use case 1 - Handling of malfunctioning machines or of complex situations

One important use case is when an automated machine faces a challenge and needs support. Challenges can be:

- The machine malfunctions
- The machine faces a situation it cannot handle.

Figure 16 A large site where line-of-sight remote control is less applicable to manage exceptions.

One approach to manage these cases has been to take control of the machines using a line-of-sight remote control and then either bring the machine out of the autonomous operating zone (AOZ) or steer the machine around the obstacle in slow speed. For larger sites, like the site shown in Figure 16, the line-of-sight remote control approach is less feasible, and teleoperation is then needed. In this case, the performance of the teleoperation system can be relatively low since it will be acceptable to operate the machine with severely limited performance during this kind of teleoperation. This also means that the latency requirement on the system, which is one of the most important properties, is moderate. Another implication of the severely limited performance is that the operator can control the machine without assistance from the machine, e.g., for obstacle detection. Since this kind of teleoperation is more of a backup, it should not be used often. Therefore, the user interface should be simple/cost effective since the teleoperator will not spend too much time doing this and the performance while doing it can be low.

This kind of solution can use simple cameras on the machine with relatively low resolution, simple gaming controls and a communication solution that is good but not does not necessarily provide very low latency. On the other hand, it is good if the solution is redundant to the normal automation system.

Use case 2 - Remote operation with high productivity

A second important use case is remote operation of machines. One such application is logging in the northern part of Sweden where the forest companies have several log terminals and want to keep them running at nighttime as well as during the day, see Figure 17. However, at night the utilization rate is low and therefore a "centralized" operator could operate the machines remotely.

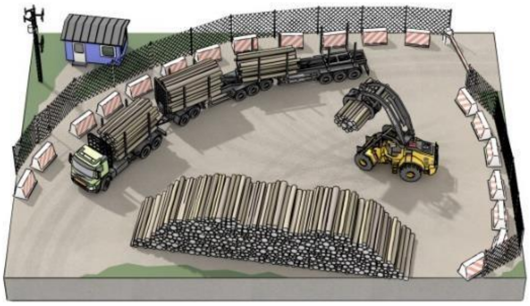


Figure 17 Log handling

In this case the teleoperator should be able to operate the considered machine, for instance a wheel loader or excavator, from a remote operator station for long periods and with high productivity. It is assumed that throughout active operation, the machine is under continuous teleoperation and when a machine is not operated it is parked in safe state with parking brake engaged etc. In contrast to the system described in use case 1, this use case implies:

- Much higher demands on the feedback from the machine to the operator
- A much more user-friendly operator station
- Support from the machine in terms of operator- assist functionality

If these conditions are not fulfilled it will be difficult and tiresome, if even possible, for the operator to maintain a high productivity without damaging the machine. This is even more important in difficult areas such as underground mining.

The use case can be further divided into two major cases, namely remote operation

- Within the same site
- From remote location not at the same site

The major, and very important, difference between these two concern the safety setup. In the first case, it is, in principle, possible for the teleoperator to do the safety check of the machine before starting the operation and to have a local emergency stop that can stop the machine. In the second case, the safety check of the machine must be carried out by an external person, and the emergency stop system must probably be transmitted through standard communication means such as internet or cellular networks.

Technology-wise this case implies much higher demands on the system than in the use case in Section 1. For example, a feedback system consisting of

- Multiple high-resolution cameras with low latency to provide a good and fast overview of the machine surroundings.
- Sensor data such as lidars to provide better depth information (very important when dumping material into pockets or on trucks)
- IMUs to provide force feedback to the operator (very important for instance when digging).

For all the systems mentioned above low latency is critical for the operator to be in control of the machine. Low latency is also extremely important in the down link, that is, from the operator station to the machine so that the machine responds to the operator's commands. In addition, there is a need for:

- An operator station with high user-friendliness. One such example is visualized in Figure 18 where the teleoperator sits in a “training simulator” that mimics the look and feel of the machine being operated.
- Operator- assist functionality such as collision avoidance, auto bucket filling or auto grading. Despite high-performing visual feedback systems, internal experience at Volvo and insights from other suppliers indicate that achieving sustained productivity over extended periods is challenging without additional machine support. One of the most crucial operator-assist functions is collision avoidance, which warns the operator and then brakes if the machine gets too close to an obstacle. Other essential supports include assistance with filling the wheel loader bucket and performing grading with an excavator. These tasks require a high level of skill when operating the machine from the cab and become even more challenging to perform efficiently when the operator is outside the cab.

Figure 18 Premium operator station for teleoperation.

It is important to emphasize that while achieving decent productivity over short periods can be relatively easy without these supporting systems, maintaining high productivity over extended periods requires them to be in place.

Use case 3 - Automation and teleoperation combined, for instance, boundary condition handling
In combined automation and teleoperation, machines can operate autonomously in some areas and be taken over by teleoperation in others to handle difficult tasks. For example, in log handling (Figure 17), challenging tasks include picking up logs from a truck and placing them on a log pile. Once the difficult task is completed, the automation system resumes control until further support is needed. In logging, this means that driving between the truck and the log pile is fully or partially autonomous. Partial automation might involve the system steering the machine along a path while a teleoperator controls the speed. When the machine approaches the log pile or truck, it requests support from a teleoperator, and once connected, operation continues. Typically, one teleoperator manages several automated machines, achieving high utilization of both machines and the teleoperator, making this a significant business case. Competitors like Sandvik and Epiroc offer similar solutions in the underground market.

From a technical perspective, the requirements are like those in use case 2. Sustained productivity is crucial, necessitating full support for the teleoperator. The system must feature high-performing, low-latency feedback, a user-friendly operator station, and automation features such as auto bucket fill and auto dig. Additionally, the teleoperation and automation systems must be tightly integrated to allow smooth handovers between autonomous and teleoperated states.

Safety-wise, there are two scenarios like use case 2: the teleoperator can be onsite or offsite. However, since machines also operate fully autonomously, onsite personnel will be needed to start up the site, ensure machine safety, and oversee safe operations, like a standard autonomous site. Therefore, safety can be viewed as an extension of existing protocols rather than a separate use case.

6.2.5 Seamless transition: autonomous to teleoperated mode (Voysys)

Background and method for teleoperation within work package V2

For challenging use cases that require teleoperation, seamless integration could enhance energy efficiency by allowing transitions between modes without stopping the machine. Scenarios with frequent switches could potentially achieve significant energy savings.

Currently, vehicles must come to a complete stop when switching from autonomy to remote operation to ensure a safe and secure handover. These interruptions cause production inefficiencies, as accumulated stoppages result in significant downtime across the fleet.

V.A.S. and Voysys formed a cohesive team, leveraging each partner's strengths from the start. Together, we investigated seamless handover of control between autonomous and teleoperated modes without requiring a stop. The investigation began with setting up a simulated solution, marking the first step toward developing this teleoperation solution and evaluating its impact on energy efficiency. V.A.S. supported Voysys in integrating their system into Volvo’s system.

Investigation of Simulation Technologies

Initially, it was assumed that using an off-the-shelf simulation solution would be straightforward, but it turned out to be a major challenge. A simulator requires:

- Physics simulation
- Graphics
- Models and scenario authoring

Much time was devoted to exploring simulation solutions based on Nvidia Omniverse and Unreal Engine. However, both ultimately proved unusable for our purposes. The third solution, a custom simulation environment based on the open-source Rapier physics engine, met our needs. Below are details on all three solutions, including notes on their usability at the time of our investigation.

Nvidia Omniverse

NVIDIA Omniverse is a collaborative simulation platform designed to enhance real-time virtual collaboration across various software environments and workflows. It leverages NVIDIA's GPU technology to render physically accurate simulations and complex 3D scenes (Figure 19). Promoted as easy to use and extremely powerful, Omniverse promised ready-made physics for vehicles and tools for creating and accurately simulating large environments.

Voysys invested significant effort in Omniverse during 2022 but found that many of NVIDIA's claims were not true at that time. Some issues encountered included:

- Omniverse was extremely complex to set up.
- It offered very little documentation for tasks outside the narrow examples provided.
- The physics simulations were slow and inaccurate (e.g., vehicles falling through the ground or "exploding" into the air).
- Debugging was difficult, and understanding why things went wrong was challenging.
- Authoring tools were confusing and lacked features.
- Scripting was slow and poorly documented.

- Using multiple camera views, necessary for simulating remote operation, made the graphics run unusably slow.

Due to these issues, we decided to abandon Omniverse and focus on Unreal Engine instead. It should be noted that as of the time of this report, Omniverse may have improved. NVIDIA is actively developing it, and our experience from 2022 could be outdated.

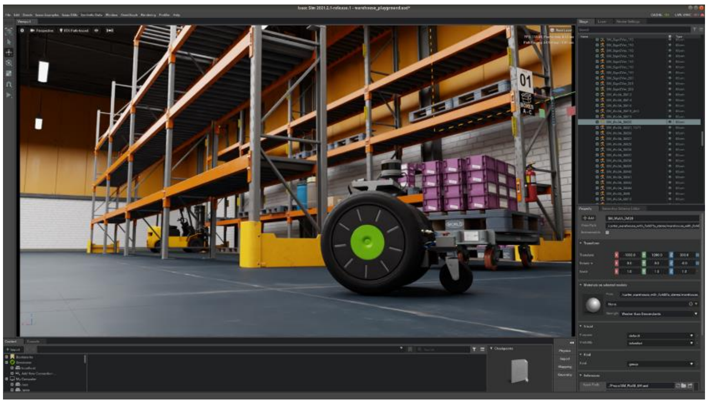


Figure 19 Nvidia Omniverse looks very polished in demonstrations but did not perform as expected and thus did not meet our needs.

Unreal Engine

Unreal Engine is a powerful and versatile game engine known for its outstanding graphics quality, often used in "Hollywood"-level productions for virtual environments. It also offers detailed and realistic physics simulations.

Although we did not invest as much time in Unreal Engine as in NVIDIA Omniverse, it was still a significant investment. Surprisingly, we found that Unreal Engine could not export multiple camera streams from the simulation simultaneously. Unreal Engine assumes a single main camera view, which is what the player sees. However, remote operation requires multiple cameras on each vehicle, making this a critical limitation for our needs.

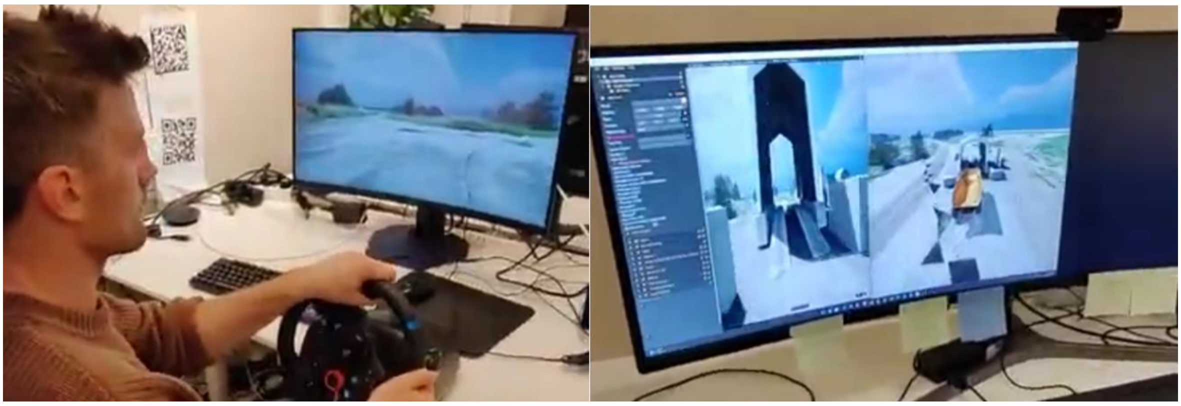


Figure 20 Daniel Olsson at Voysys, using the Unreal Engine simulation environment. Ultimately this proved too slow to be a viable option.

Exporting more than one camera proved to be unworkably slow. On a powerful computer with an RTX-3080 GPU, we observed frame rates of 10-15 frames per second for relatively simple scenes, with the GPU fully loaded. This was a surprising result, and it is possible that we made an error, as Unreal Engine is a well-regarded software and should theoretically support our needs. However, after spending weeks on this issue, we decided to tentatively explore other options.

Custom Simulation based on Rapier Physics Engine

At the start of the project, Voysys already had an in-house developed graphics engine, the Oden software, which included some scenario authoring tools. This software featured a plugin for adding physics simulation, model rigging, and more scenario logic (Figure 21). We decided to integrate the open-source Rapier physics engine as a plugin to the Oden software.

The Rapier physics engine, written in the Rust programming language, is designed for high-performance, real-time simulation of rigid body dynamics, particularly suited for gaming and virtual environments. It focuses on robustness and precision, enabling accurate simulation of complex interactions and collisions in virtual scenarios.

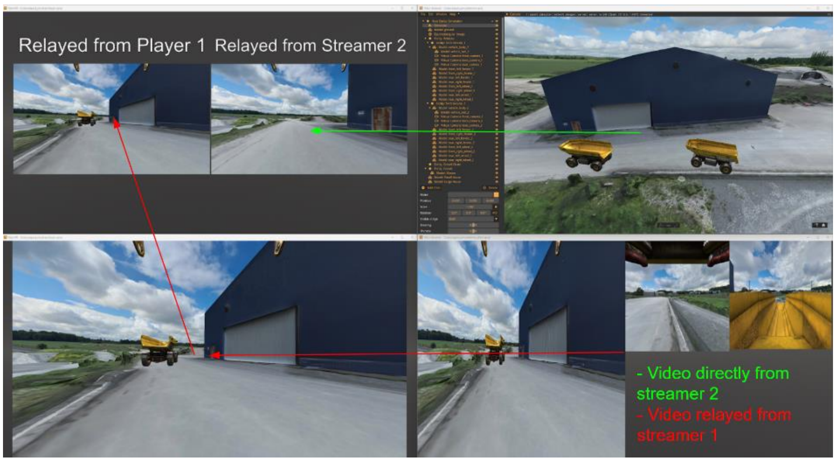


Figure 21 The custom simulation based on the Rapier physics engine, which was what was finally selected for use in the ASPECT project.

After a week of working on this integration, we made more progress than during the entire time spent on Omniverse and Unreal Engine. Consequently, we abandoned all other simulation efforts and, by mid-2023, decided to proceed exclusively with this custom solution.

The simulation environment as built and used in the ASPECT project supports:

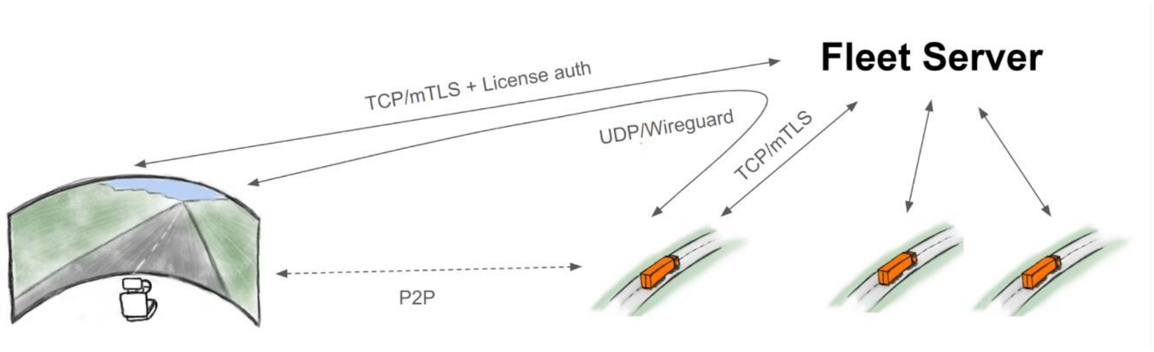
- Realistic physics simulation (without “explosions” or things “falling through the floor”)
- Upwards of 20 virtual cameras
- Tested with 8 vehicles simulated in the same shared simulation environment
- Four independent remote operators operating vehicles in the same simulation
- Waypoint based autonomous navigation system
- Ability for a remote operator to take over control from the autonomous system, and hand back control
- Ability for an “orchestrator” role (human), to assign vehicles to routes and hand them over to remote operators (all in simulation)

Connection Management and Fleet Server

To reach the objectives of the project, a method for operators to connect to virtual vehicles in a simulation environment was needed. This required some service that lists vehicles and facilitates the connection between operator and simulated vehicle.

One output of the fruitful collaboration between Voysys and V.A.S. was the development of a “coupling server” (a.k.a. fleet server) that lists available vehicles to the operators, including if the vehicles are being actively operated or if they are under autonomous operation. The coupling server sets up secure connections between the operator and vehicle in a cryptographically correct way.

The fleet server was used to monitor all vehicles on site as well as establish connection to each vehicle. This server facilitates easy control of the vehicles, enabling operators to remotely monitor fleet activities and intervene when manual control is necessary, for example due to unexpected events which the autonomous system would not be able to handle or security concerns. Connections to the fleet server are coupled via mutual Transport Layer Security via Transmission Control Protocol (mTLS/TCP) for security at the Transport layer as well as licensing and identification of the vehicle or operator through the Oden license system. Connections are established via the TLS connection to the server and if the connection is successful a User Datagram Protocol (UDP) connection is established using Wireguard for the video and data traffic. The use of Wireguard ensures that the traffic is encrypted end to end in a secure manner. In addition to the connection management the fleet server enables monitoring of several vehicles by relaying the video information from a vehicle to all other operators that want to monitor a vehicle without additional vehicle to source bitrate, which is essential at bad network conditions. The video is also relayed back to the server to ensure that the controlling connection is not disturbed in any way due to monitoring as well as ensuring the best possible latency through Peer-to-Peer (P2P).



The fleet server was integrated into the existing Voysys remote operation system through the existing plugin system as a fleet plugin. The server can be run standalone from the Oden system as a backend service.

Tests and Evaluations

Obtaining accurate data on energy consumption for the studied vehicles in the ASPECT project was difficult. Energy consumption was therefore based on assumptions and the tests were mainly focused on large scale autonomy/remote operation handovers. One complicating factor is that the friction coefficient varies tremendously between sites. Sites with mud and deformable grounds require vastly more energy when stopping and starting vehicles.

Multiple tests were conducted using 1-4 remote operators. There were also tests using different numbers of vehicles. These tests both focused on the efficiency of handover between remote operation and autonomy, and on the overall efficiency of a site with different numbers of vehicles per remote operator. Figure 22 shows the data as a plot of how much goods could be transported with different vehicle to operator ratios.

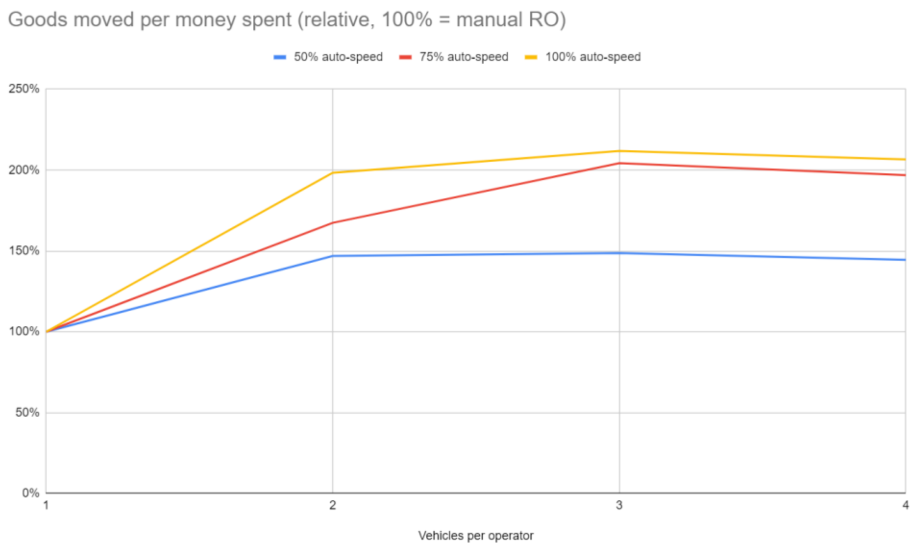


Figure 22 The conclusion of the tests is that there is an ideal operators per vehicle ratio for a mixed remote operation / autonomy system. Under the used assumption the optimal appears to be 3 vehicles per remote operator.

Result

Our results indicate that there is an optimal ratio of vehicles to remote operators for each site and its local conditions. Experimental results from simulations with up to four active simultaneous remote operators show that, for the tested scenarios, the optimal ratio is three vehicles per remote operator. This achieves the highest ratio of goods moved per money spent, factoring in the cost of remote operators' salaries. Note that this metric is highly dependent on the efficiency of the autonomous system, which was very basic in the tested scenario.

Stopping and starting a vehicle leads to energy losses. While electric vehicles have regenerative brakes, they only work up to a certain maximum braking force. If the autonomous system signals that human remote intervention is required, there could still be braking losses. Additionally, there are losses due to friction and motors not operating at 100% efficiency. For diesel-based vehicles, starting from a standstill consumes much more fuel than continuous motion, and no energy can be regenerated during braking. Therefore, the benefit of seamless handover in terms of energy and CO_2 emissions is more significant for diesel vehicles than for electric ones.

By eliminating the need for vehicles to fully stop during a handover process, idle times are reduced, thus increasing productivity. While this might save energy by avoiding stops, regenerative braking systems can recover most of the energy typically lost during stops. The main benefit for an electric transport system lies in the reduction of idle times. In contrast, for a diesel-based system, a seamless handover can significantly reduce energy waste by avoiding multiple stops and starts, as well as reducing idle times.

Future studies should focus on implementing teleoperation systems with real vehicles to validate the simulations and frameworks developed in this study. Real-world testing will help understand the practical challenges and effectiveness of seamless handover mechanisms, fleet server robustness, and overall system integration.

6.3 V1 – TAXX AND A SYSTEM OF ELECTRIFIED MACHINES

6.3.1 Objectives and goals

The objective of work package V1 was to continue developing the system of electrified machines for Volvo’s confined area autonomous transport solution (CAATS) as well as design a new Volvo medium-to-large electric hauler TAXX along with charging technology and charging infrastructure. Work package V1 would also develop relevant simulation and machine models to be used for the design and in the digital twin developed by BTH in work package H4.

The key objectives and their status are summarized in Table 6.

Table 6 Objectives for work package V1.

Key objectives	Status
Design the TAXX - a larger electric machine (dumper) that meets energy and productivity requirements. Validation and verification in a digital environment; mechanical validation in a computational environment.	Completed. Demonstrated through AR goggles during final demonstration at AstaZero. Information is confidential and details will not be included in the report, only concepts and key requirements or considerations.
Design a battery system that meets large energy and peak power requirements while	Completed. Developed on the Volvo Group electromobility platform, configured to meet the needs

reducing the size and enabling a larger payload with reduced cost	of the TAXX. Upgrade of the smaller TA15 has also been considered.
Create a digital twin of the TAXX machine, that can be used for optimization of site planning and real-time energy optimization.	Partly completed. Digital twin and site simulation model created by BTH in work package H4. Input to machine models for TAXX provided for site planning. A digital twin cannot be validated until the physical counterpart has been built. Real-time energy optimization through digital twins is not feasible or prioritized currently.
Design automated charging stations to transfer large amounts of energy in a short time.	Partly completed. Commercial state of the art identified as well as components to be used for TAXX. Physical integration, verification and validation to be done later. Automated charging stations for the TA15 are in use and functioning, using an inverted pantograph solution.
Design an infrastructure for e.g. ramps where charging can take place while the machine is running (e.g. driving uphill loaded)	Not complete (scope change approved). State of the art described. Not currently practical or prioritized, although of interest in the long term.

There have also been learnings for the smaller TA15. V.A.S. has identified the need for upgrade of certain electromobility components to increase the machine's performance. However, the basic concept of the TA15 is set, including the charging infrastructure. We briefly touch upon certain aspects to set the TAXX in context relative the TA15.

An overview of the key deliverables and their status is provided in Table 7.

Table 7 Key deliverables for work package V1.

Deliverable	**Status**
Method for requirements management at machine level for different applications; for electrified autonomous transport systems.	Completed. Volvo CE applied different methods, including multibody models, to evaluate different design options for the TAXX, based on the expected application of the system.
Technical solutions for the TAXX energy systems, subsystems and on site.	Completed. Electromobility design for the TAXX machine is completed. Technical solutions for charging methods and infrastructure have been identified and evaluated. Different options are available and will depend on site-specific requirements.
Method for formal and non-formal verification and validation of machine models	Completed. Part of the systems engineering SW/HW development methods and the TAXX design methods.

6.3.2 Operational design domain for the TAXX

To design the TAXX, the requirements that it must fulfill as an autonomous electric hauler in a mining context must be understood. The TAXX has been designed based on a cross-section of prospective customer cases. The physical properties of a typical customer site were identified.

- Haul routes - distance, inclination, elevation differences
- Road conditions (friction, curvature)
- Speed
- Ambient temperature and weather conditions

We also needed to understand the typical productivity demands in terms of transported tons per hour or load cycle. A load cycle is defined as loading – transport – unloading – transport - loading. Examples:

- Inclination of haul routes - max 10%. The TAXX should therefore be expected to perform continuously in that range, both uphill and downhill. In addition to traveling at a certain speed uphill or downhill, we also had to make sure that the TAXX could stand still on an incline, fully loaded, in case of pause or emergency stop.
- Distance and elevation - haul routes can vary from hundreds of meters to several kilometers with elevation differences of several hundred meters. Some open pit mines are compact and deep, whereas others stretch out across large surfaces.
- Ambient temperature - mines and quarries can be found in arctic as well as tropical regions, with temperatures ranging from -40°C to + 50°C
- Climate - conditions ranging from dry and dusty to icy blizzards or pouring rain.
- Mines and quarries are often dusty and dirty with rough roads. This places high demands on robustness of sensitive on-board electronics, as well as on the ability of navigation and communication devices to function under variable conditions.
- Mixed traffic at high speed, vulnerable road users.

The aim is to have a machine that can perform transport missions in a wide section of the mining industry, as part of a profitable autonomous transport solution.

6.3.3 Designing the TAXX – key challenges and factors to consider

Designing a brand new medium sized electric and autonomy-enabled hauler for the mining segment has not been done before in Volvo. There are many lessons learned from the smaller TA15, but the target environment is different for the TAXX and the electromobility challenges are higher due to the requirements on increased payload, higher speed and longer distances.

Since TAXX is a new concept, there is little historical data and experience on which to base the design. Without a reference or prototype, the project had to rely heavily on simulation-driven development, integrating relevant information from non-electric and non-autonomous machines.

The TAXX needed to be designed within Volvo-specific boundaries and limitations while addressing the needs of potential customers. Being among the pioneers in developing this type of autonomous electric solution for the mining and quarry industry presents its own set of challenges. The physical conditions vary significantly, including factors such as temperature, distances, payload, and core infrastructure like roads and electricity. The market is in an early stage of innovation and the early adoption of new technology, which means that practical and commercial conditions can change rapidly. At the same time, the industrialization process for large machines involves long lead times and is not always compatible with more agile software development. Design decisions made today can impact the final autonomous transport solution for many years. Therefore, it is crucial to identify which design decisions for the TAXX are most important in terms of productivity, energy efficiency, maintainability, reliability, and the total cost of operation and ownership.

The project also needed to consider how to enable the industrialization of the TAXX by leveraging the full production and logistics capacity of the Volvo Group. The design of the TAXX had to align with the boundaries of Volvo Group's electromobility strategy and plans. While theoretically, a more energy-optimized TAXX could be designed, commercializing it on a larger scale would require significant additional investments and pose a higher risk of logistical complications.

Key factors that were considered in the design of the TAXX:

- Physical conditions for operation (temperature, weather, road conditions)
- Configuration of the electric powertrain (transmission, axles, battery energy and power capacity)
- Payload vs total weight
- Physical location of the autonomous driving kit components on the TAXX base machine
- Speed, distance, productivity, tractive effort
- Loading equipment
- Vibrations, strength and durability
- Charging technology and charging time (total standstill time per charging event)

Details of the TAXX are confidential so this report will present high-level design considerations and findings. A VR-representation of the TAXX was shown in the final demonstration event at AstaZero, where participants with VR-goggles could “walk” in and around the machine to view it in full (Figure 23).

Figure 23 Participants at the demonstration event viewed the TAXX with VR-goggles. By pointing and clicking with the remote control, the users can position themselves in different parts of the TAXX, to view the machine and its components from different angles and positions, even from within the machine.

6.3.4 Method for verification and validation of machine models

A model is a representation of something, such as a machine, but it can also be a model of certain characteristics. The type of model you create depends on the purpose of the model.

A model is often used to simulate different scenarios or events. This is cheaper and faster than building and testing the real product and allows for changes earlier in the design phase. For example, a computer simulation using a digital model allows you to execute a scenario thousands of times while changing one or more variables to assess the impact. In essence, the simulation models for machine models consist of a set of mathematical equations describing the laws of physics. Depending on the machine performance or characteristics of interest to investigate/resolve, the need of model resolution varies. A digital twin is an accurate model of its physical counterpart in a digital environment. A digital twin needs to be validated, e.g., by gathering information from the physical counterpart and transferring it to the digital model to increase its consistency.

In 2023, V.A.S. inaugurated a new test site at AstaZero, near Borås. The site contains all the main features of a real site, such as loading and unloading areas, a charging station and haul routes with different inclinations (see Figure 24). In addition to this site, there are test sites in Eskilstuna and Säve.

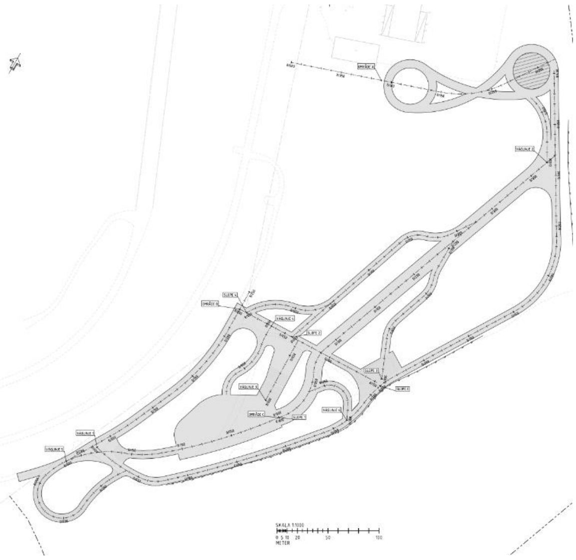


Figure 24 Layout of the AstaZero test site for the Volvo autonomous transport system (left picture). There is a "figure eight" track near the control tower (top right) for shorter load cycles. There are also several longer paths with different inclines leading up to a loading and charging area (bottom left). A digital twin of the test site is shown in the picture on the right.

The digital twin of the AstaZero test site is used in the V.A.S. inhouse hardware-in-the-loop (HIL) and software-in-the-loop (SIL) simulation environments (see Figure 25). When running the autonomous fleet at the test site, data can be collected from each vehicle's various on-board computers and the Site Control & Monitoring sub-system. By comparing the data with its simulated counterpart, discrepancies in the simulation environment and/or the machine models can be identified and resolved. Thus, there is a feedback loop between the simulated environment and the real environment, leading to improved machine models, improved software in the autonomous transport solution, more efficient code development, less expensive and time-consuming testing and less need for real machines or vehicles in testing.

Machine models for TA15 performance in a site have been developed and validated in the V.A.S. simulation environment, since real-life data is available for the TA15. By understanding how the TAXX differs from the TA15, the concept developed for the TA15 machine models can be reused and adapted to the future TAXX. This will be relevant to verify that the different software subsystems in the autonomous transport system work together with the new TAXX, or to identify gaps that need to be resolved.

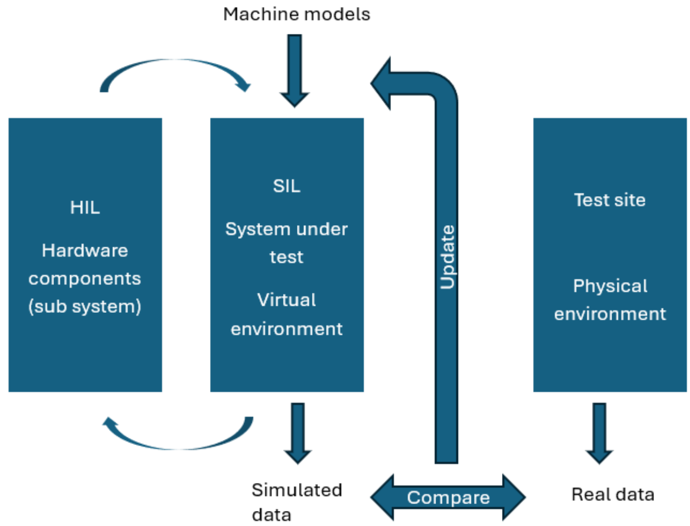


Figure 25 Illustration of how data from the VAS simulation environment is compared to data from the real test environment and the result is used to update the machine models. The HIL environment is used to verify hardware components and their software. The SIL environment simulates the system for one machine or vehicle – the rest of the fleet are pre-defined non-player characters. The HIL-SIL bridge allows closed-loop simulation, where responses are fed between HIL and SIL.

Machine models for the TAXX as applied to a site and fleet scenario have been developed and used in the digital twin developed by BTH in work package H4 but cannot yet be validated since no there is no physical counterpart or real-life data available yet. To support the design choices for the TAXX, the impact of alternative designs and components on machine performance was evaluated using other modelling and simulation. There are some experiences from the smaller TA15 and the existing articulated hauler machines that could be applied to the TAXX design questions. However, considering both the unique machine concept and the new target of operation, there are many aspects where experiences from existing machines are not applicable. With virtual models of systems or a complete machine, it is often possible to evaluate a concept in early phases before physical prototypes are available. In the following sections, both the estimation of road profiles and different models developed for TAXX are briefly described together with examples of machine performances analyzed.

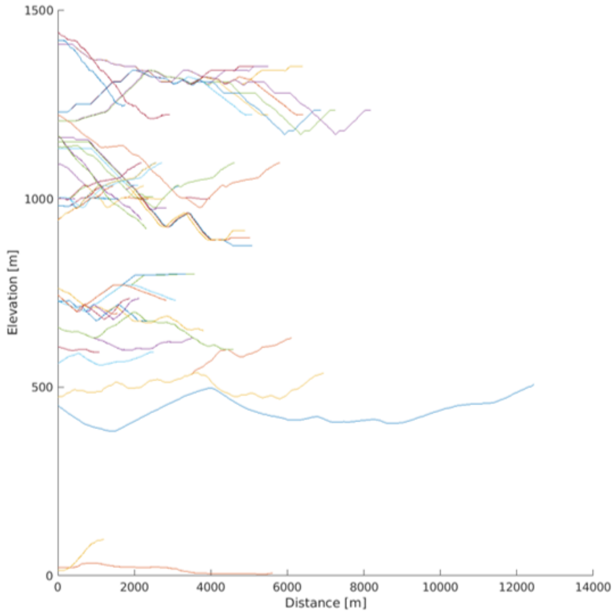


Figure 26 Haul route topography from multiple sites.

6.3.5 Site performance model

To investigate and compare machine performance with respect to range, energy consumption and productivity in different load cycles, a one-dimensional machine model was developed in MATLAB. The model was created for early project phases, when limited information was available about system and component characteristics. The input to the model describes the basic machine properties, power capacity and losses of key components. Based on the input, the model velocity, energy- and power consumption was predicted along the trajectory, also considering potential velocity limitations due to trajectory curvature and inclination. A simplified machine representation enables fast iterations to investigate and to compare alternative concepts but comes at the expense of accuracy. However, in project phases when detailed information is not yet available, there is great value in early assessments.

We had limited experience from the site profiles in which the TAXX is intended to operate since this is a new industry segment for Volvo. To estimate realistic customer site conditions in simulation, information from approximately 60 trajectory profiles available from real sites within mining and quarry were utilized. The site data has provided knowledge about variation of e.g. load cycle distance, distribution of road curvature and elevation profile (Figure 26) and has been used in simulations to predict and evaluate machine performance.

6.3.6 Multibody simulation model

To achieve a high-resolution analysis of the machine's dynamic characteristics and force distribution in the load-carrying structure, a multibody model was created using ADAMS software. This model comprised flexible bodies (parts) based on CAD and mass information, interconnected by constraints.

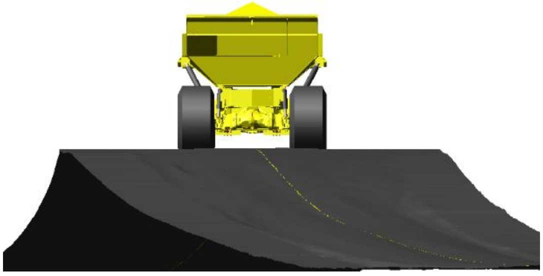


Figure 27 Screen shot from a multi-body simulation.

The multibody model was co-simulated with a detailed tire model, essential for accurately representing machine dynamics. Additionally, the hydraulic system—including suspension, hoist, and steering cylinders—was modeled separately in MATLAB Simscape and co-simulated with the ADAMS model. Figure 27 shows what the multi-body simulation of the TAXX can look like in the ADAMs environment.

6.3.7 Strength & durability loads based on customer trajectories

The design must withstand the environment in which it is intended to operate. The multibody model was employed to simulate events that could potentially generate maximum loads in load-carrying components, allowing us to evaluate the strength of the structural components.

To assess the fatigue properties of these components, we needed to estimate the load spectrum for a machine operating in a new customer application. By utilizing trajectory data from customer sites (as previously shown in Figure 26), which are representative of the TAXX's future operations, we could estimate the velocity and power profile of the TAXX in a customer environment.

To translate these conditions to our internal test tracks, we identified a combination of test tracks that best matched the real customer sites' driving conditions. The multibody model was then simulated on virtual internal test tracks, which featured detailed road roughness resolution. The results from these simulations were combined into a load spectrum based on the identified combination of test tracks, accurately representing the customer conditions derived from the customer trajectories (Figure 28).

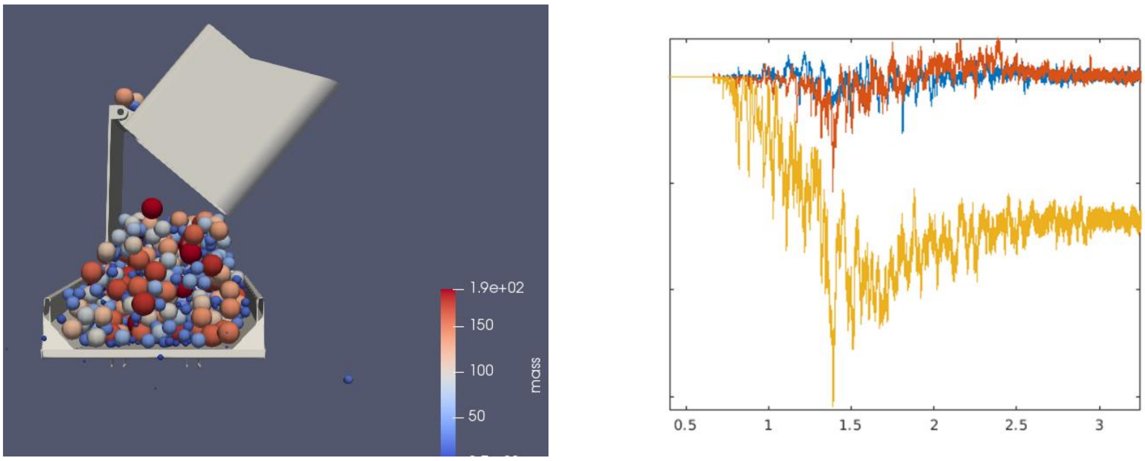


Figure 28 Left figure: example of potential dimensioning max load event when using a matching load unit bucket to fill the body in one sequence. Right figure shows the load time history, i.e., how the forces on the bucket vary over time.

6.3.8 Tires and maximum speed

Choosing the right tires is crucial for a machine that needs to travel quickly while carrying a heavy load. The available tire options and their characteristics must be carefully considered, as tires can be a limiting factor.

Balancing traction force and maximum speed is essential to create a machine specification suitable for mining and quarry operations. A high maximum speed allows the machine to transport material faster, potentially increasing productivity. However, at high velocities, the traction effort may be insufficient to reach the target speed if rolling resistance and inclination are high. In such cases, the power delivered by the electromobility platform must be increased to maintain traction performance at maximum speed.

Additionally, tire specifications can limit velocity, meaning that maximizing speed may not always enhance productivity. Higher speeds generate more heat in the tires, influenced by the tire rolling resistance, the payload, and the machine's total weight. Excessive heat can lead to increased tire wear and the risk of tire explosion. Tire performance directly impacts energy efficiency, productivity, and cost. Finding the right balance to meet the operational requirements of mining and quarry customers is a significant challenge.

6.3.9 Payload vs total weight

Transporting non-productive weight is a waste of energy. A heavier payload requires more energy for transportation, and larger energy storage means larger batteries, which increases non-productive weight. Therefore, maximizing the payload and using larger batteries may not always be the best approach.

One of the design challenges has been finding the optimal compromise between total weight and transported weight, considering stakeholder requirements and the "Elephants to Ants" philosophy. The design process began with an idea of the optimal payload versus total weight, but the final result is an iterative consequence of decisions made along the way. In this report, we refer to the payload as XX, as this information is not yet public.

6.3.10 Choice of loading equipment

The choice of loading equipment significantly impacts the geometry of the machine's basket. For instance, a wheel loader can load from the side, allowing it to approach the TAXX and load evenly from both sides. In contrast, an excavator may need to approach from the tailgate to reach the farthest point of the basket, necessitating an overhang at the tail end of the TAXX to allow the excavator to get as close as possible. This is not as challenging for the TA15, since it is smaller in size and can therefore be filled more easily by the loading equipment (Figure 29).

This overhang leads to uneven pressure on the two axles, increasing wear and tear. Consequently, using an excavator as the loading tool limits the maximum payload allowed, compared to a wheel loader. This example illustrates how the choice of loading equipment can impact productivity in terms of payload per trip. By carefully selecting the appropriate loading equipment, we can optimize the machine's productivity and ensure its longevity. However, we must also consider the available loading equipment and the overall safety case and certification of the product and solution.

Figure 29 TA15 loaded by excavator (left) and wheel loader (right).

6.3.11 Simulation support for functional development

When developing the base machine for an autonomous application, there are new aspects within functional safety to consider compared to a manual operated machine. How should the machine act if a function fails and cannot be activated, or the opposite, is unintendedly activated? The consequences of a failure must be handled at the machine level from a software perspective, which is something new compared to traditional machines.

Figure 30 illustrates a simulated scenario of a failure in a brake circuit, resulting in application of full brake on the front axle, which has not been predicted by the autonomous system. In the figure, the front axle brake is activated at the location when the machine reaches the yellow rectangle. The three parallel views represent the same machine at different velocities. The outcome from the simulation was used to determine stop distance in lateral direction relative to the planned path (Figure 30). With a known lane width, the max allowed velocity in a specific curvature can be identified to avoid the risk of entering the oncoming lane.

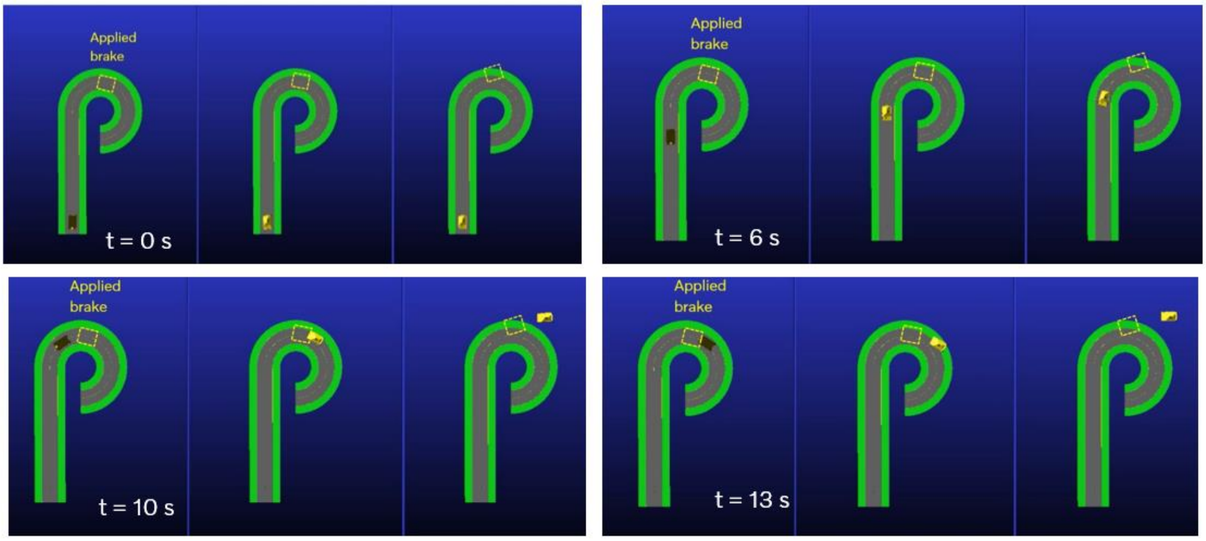


Figure 30 Simulation of failure in a brake circuit to determine stop distance in lateral direction relative to the planned path.

With detailed representation of machine dynamics and the steering, the multibody model has also been used to evaluate functions under normal operation, e.g. to check that the hydraulic steering performance is fulfilled according to ISO requirement.

6.3.12 Vibration environment of electric components

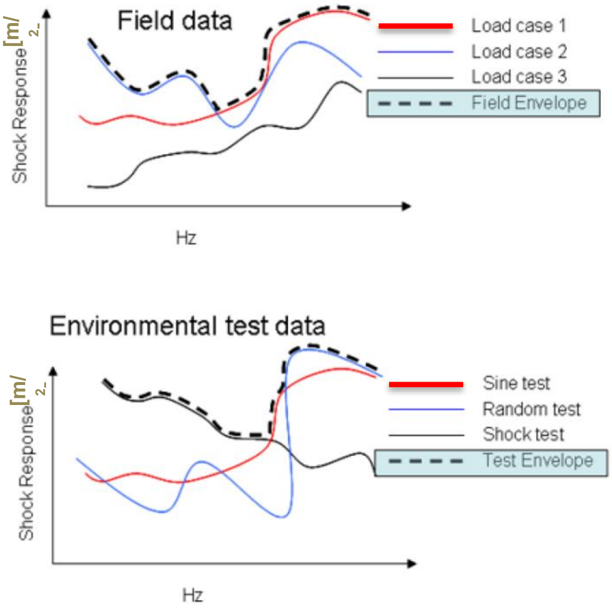


Figure 31 Output from component frequency tests.

Along with electromobility and autonomy, many new electric components are introduced in the TXX machine. Electric components are most often tested according to a standardized vibration environment to guarantee their functionality. By comparing the component’s specification to the environment where the component is mounted on the machine, the risk of failure can be estimated. The component specification is typically defined within the range from a few up ~2000Hz or even more. The 3D multibody model has limited dynamic resolution in the frequency range. Results from simulations can therefore only be used to evaluate the low frequency range vibration spectrum. Nevertheless, for components where low frequencies are critical, the simulated vibration environment is relevant (Figure 31). The excitation at the component´s mounting location is exported from the simulation and compared to the component specification. It is not realistic to capture or represent the complete specification frequency range in simulations. The level of details required would make the model too complex. Measurements are needed for those cases, which means that the physical prototype must be built to evaluate the higher frequency vibrations’ impact on the electronic components.

6.3.13 Electric powertrain

Within the Volvo Group, all diesel-driven machines and vehicles are based on a common platform to leverage synergies across different brands and products. Similarly, an electromobility platform is being developed to support the new generation of electric machines and vehicles. Consequently, the TAXX needed to be designed within the boundaries of the common Volvo Group electromobility platform and toolbox. One challenge for the project has been maximizing the Volvo electromobility platform for the TAXX, given its specific performance requirements. Different choices in electromobility components were available, such as:

- Power Capacity: Governs the machine's velocity, both for tractive and regenerative efforts.
- Charging Power: Minimizes downtime during charging.
- Energy Capacity: Defines the range of the load cycle.

The transmission is primarily designed for long-haul trucks, offering more capacity and durability than the TAXX requires, making it somewhat overdesigned for the TAXX's needs. A long-haul truck and the TAXX use different numbers of components from the electromobility toolbox. For instance, a truck has one gearbox connected to one axle, driving two electric engines, whereas the TAXX is designed with two gearboxes, one per axle, driving four electric engines in total. There is no front or back on the TA-series in terms of electromobility, providing greater freedom in planning an energy-efficient path and driving pattern.

The choice of components from the electromobility toolbox impacts the power output. Examples include components for DC-DC conversion to run the electric engines and recharge from the axles back to the batteries, and the type of battery used (considering weight, size, and power/SOC window).

Ultimately, how we use the platform for the TAXX depends on the traction force and driving momentum required at different speeds. By carefully selecting and optimizing the components the electromobility toolbox, we can ensure that the TAXX meets its performance requirements efficiently.

6.3.14 Batteries and state-of-charge

Optimizing battery characteristics and lifetime is a competitive advantage for electric and autonomous vehicles. The type and number of batteries for the TAXX were determined based on requirements for, e.g., speed, charging cycles, payload, total weight, distances and inclinations. Ultimately, the decision revolves around balancing total energy and power output against weight, as well as determining the optimal state-of-charge (SOC) window. Energy refers to the capacity to do work. In the context of a BEV battery, it indicates the total amount of electrical energy stored, determining the vehicle's range. A higher energy capacity allows the vehicle to travel further on a single charge. Power is the rate at which energy is used or transferred, indicating how quickly the battery can deliver energy to the electric engine. It affects the vehicle's performance, such as acceleration and top speed. Higher power enables faster acceleration and higher speeds.

A critical aspect for the TAXX machine concept has been to investigate the number of batteries needed, as this influences cost, design, and geometrical packing of components. The number of batteries sets the available onboard energy, thereby affecting the load cycle distance and the ability to maintain speed if the battery output power is a limiting factor. Using the one-dimensional (1D) MATLAB model described in section 6.3.5, machine performance has been evaluated on customer site trajectories, which represent realistic site profiles and show variations across different trajectories.

Additionally, the 1D-model (Figure 33 and Figure 34) provides power-time history data, which is used to dimension the high-voltage system and the active cooling system.

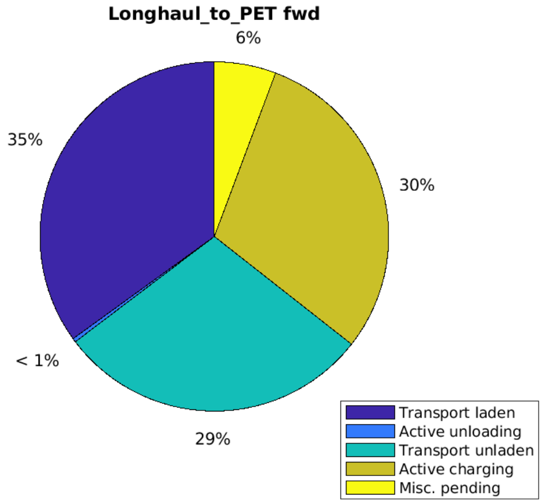


Figure 32 Time distribution for one load cycle for the trajectory "Longhaul_to_PET fwd", starting with Transport laden.

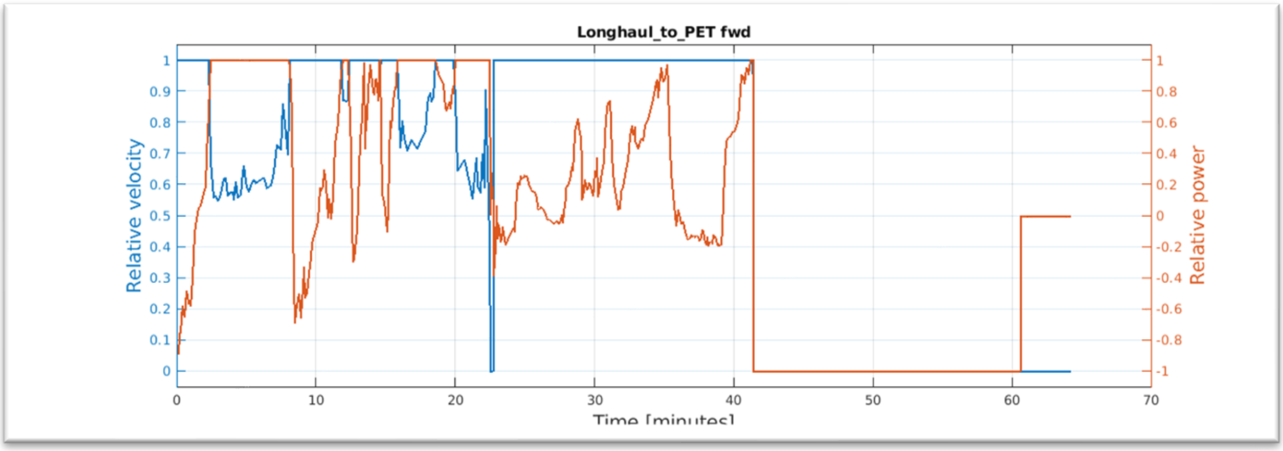


Figure 33 Velocity and power as a function of time. This illustrates how power is the limiting factor when the velocity is not at maximum. When the machine reaches peak velocity, less power is used to maintain velocity. The progression from left to right matches the load cycle in Figure 32, starting with transport laden, followed by unloading, transport unladen, charging and miscellaneous idling.

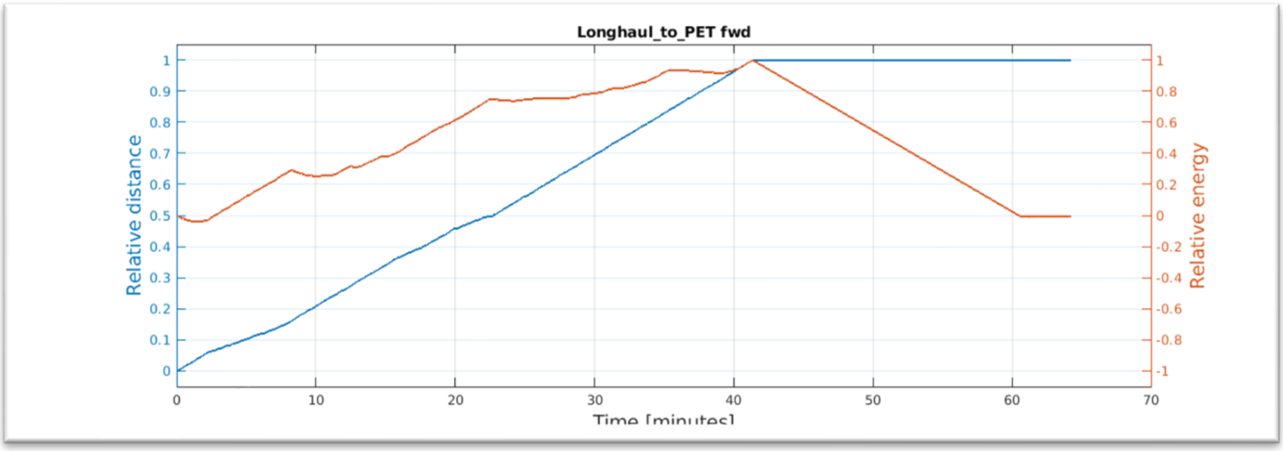


Figure 34 Distance and energy consumption as a function of time.

A new battery has a maximum available energy when fully charged. The state-of-charge (SOC) indicates the battery's charging status, i.e., the energy available for use. The battery can receive and deliver varying amounts of energy depending on its SOC. At high SOC, the battery cannot receive as much power as it can at lower SOC levels. Conversely, at low SOC, the battery cannot deliver as much power. The battery charges faster in the middle SOC ranges than in the upper ranges, meaning that beyond a certain SOC level, charging efficiency decreases.

The SOC window defines how much of the available capacity of a battery can used and thus impacts the charging patterns. It sets the lowest and highest SOC levels allowed for the battery. For example, if the maximum is 100% and the minimum is 0%, we might choose a SOC window of 20% - 70%. By avoiding the extremes, long-term performance and battery life are improved. However, utilizing a wider SOC window allows for a longer transport range. Figure 35 illustrates these concepts, showing the impact of the SOC window and battery degradation on available energy.

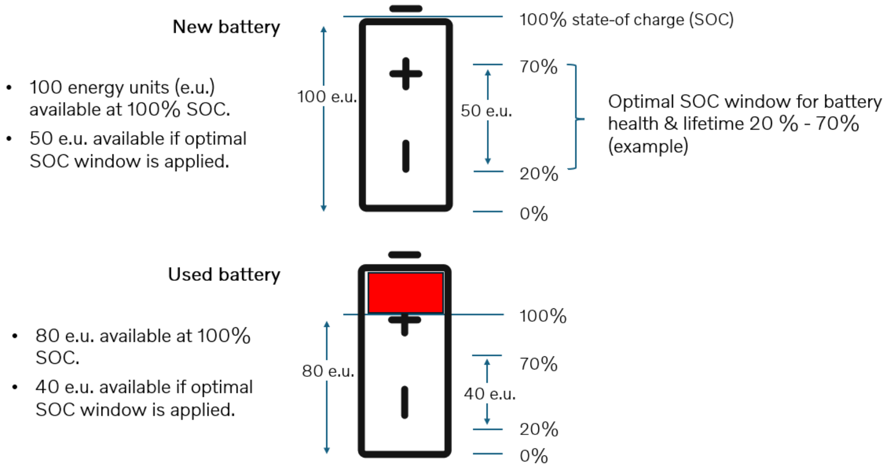


Figure 35 Illustration of the battery capacity and state of charge when new or used.

We need to consider battery degradation over time and the number of hours of use or charging cycles before replacement is necessary. One advantage of the "Elephants to Ants" philosophy and offering transport-as-a-service is that machines and vehicles could be relocated to customer sites with lower battery performance requirements, such as those with shorter loading/charging cycles, while still maintaining required productivity levels. This ensures a better utilization rate of the BEVs and their batteries over their lifetime.

Battery performance and lifespan are sensitive to both ambient and internal temperatures. Discharging the battery generates heat, and high cell temperatures accelerate performance degradation and shorten lifespan. To address this, the TAXX includes an active cooling system. Although the cooling system consumes energy, its benefits in preventing energy loss, power reduction, and premature battery replacement outweigh the costs.

The TAXX will regenerate energy and charge the battery when braking, for example during transport downhill. If loaded, it will regenerate more than if unloaded. To be able to regenerate the energy, the battery state of charge must be in a state low enough to be able to receive the energy. If not, the energy must be converted to heat and ventilated, which is not energy efficient. Such a ventilation device requires additional volume and weight on the machine. Even though a TAXX is equipped with mechanical brakes, the electrical braking system is the primary brake. A cooling system for the mechanical brakes to avoid overheating also requires volume and weight on the machine. The most energy efficient solution is therefore to ensure that the SOC window and charging pattern for each specific site is defined to enable regeneration of energy to the batteries while braking the TAXX. Figure 36 shows a generic example of energy curves for a machine, indicating how far it can travel uphill or downhill, loaded or unloaded, at different inclinations and with a specific battery capacity. For example, with an inclination of 0.08, a loaded machine can travel downhill 2700 meters but only 800 meters uphill.

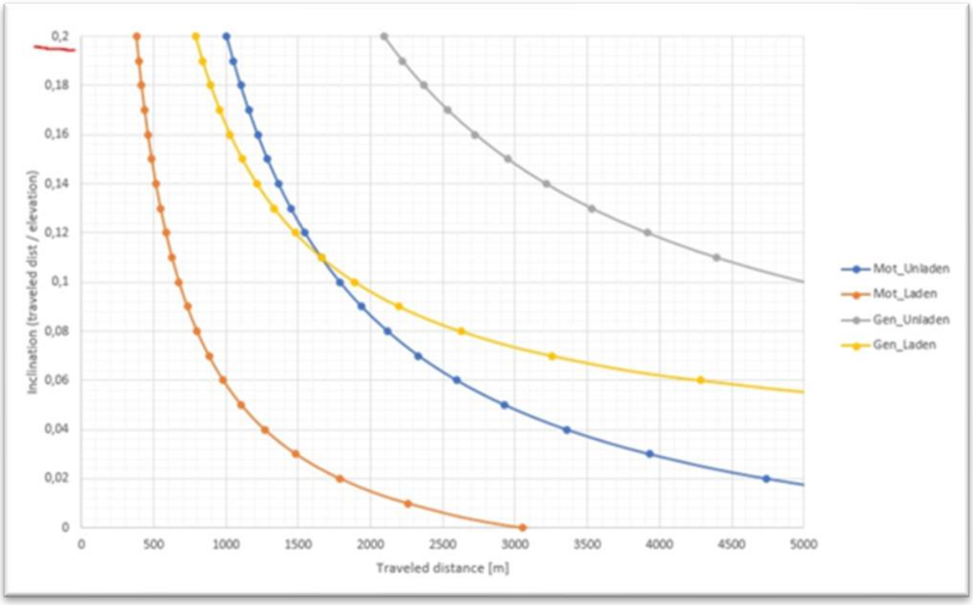


Figure 36 Example of energy curves for an electric machine showing how far it can travel on one charge depending on inclination of the haul route and whether travelling loaded or unloaded, uphill or downhill. Gen = generate energy = travel downhill. Mot = motor = travel uphill.

There is not yet enough data to extrapolate from to know what the right SOC window is for the different applications of the autonomous transport solution. We are limited to physics, mathematical equations, and empirical findings from similar applications.

There are a few possible choices for managing the SOC windows, such as:

1. Do not limit the SOC window at the machine level. Instead, let the autonomous system define the SOC window based on input data such as the physical site layout and temperature.
2. Set one fixed SOC window at the machine level.
3. Allow a few different SOC windows for different ODDs (enabled by a “switch”). For example, a site with short distances but steep inclines or a site with long distances and less steep inclines.

To guarantee a certain performance within the stated operational design domain, option three will be used. This sets the SOC window at the machine level. On top of that, the Site Control & Monitoring system can define the charging patterns and a narrower SOC window, if relevant for a specific site.

6.3.15 Charging technologies and infrastructure

The autonomous hauler will be used in large-scale quarrying and mining where it will charge regularly after one or multiple haul cycles. Therefore, a high-power DC charging station with a robust, automated connection device is needed. Depending on drive cycles and the amount of energy in the batteries, different charging powers can be considered. The minimum recharging power for smaller machines is 150 kW, for bigger machines it can go up to 1 MW. There are no known electric autonomous haulage systems deployed on a larger scale, so the project had to design a suitable charging system. There are several suppliers who can provide sub-systems (described below), but the integration and final commissioning must always be performed for each site and deployed individually.

The TAXX has been designed so as not to limit the future choice of charging solution, even though the final decision has not been made.

Charging can be done conductively or wirelessly (inductively):

- A conductive system includes a charging station and an automatic charging device (ACD) where we have considered the scope to be *Grid to Inlet*. This means connection to the grid, charging station and included components (cooling, mechanical, enclosure etc.), automated connection device, cable and plug. We have also considered the need for some custom inlet on the vehicle. We can divide the suppliers into suppliers of ACD solutions and suppliers of charging stations. Some of them are working together to deliver both as a complete package, while others provide a charging station or an ACD separately.
- An inductive (wireless) system includes charging station, charging pads on the vehicle and a charging slot.

Charging at lower power can be beneficial for battery life but means a longer period of stand-still. This is therefore an option mainly for operations that are not continuous. The TAXX is designed for the mining industry, where operations are often 24x7. Therefore, a lower power charging is not relevant and has been excluded from the design.

6.3.15.1 *Conductive system ACD - Pantograph solution*

The pantograph solution is well known from recharging of buses and has been derived from use in train and tramway application. The classical system is mounted on the roof of the vehicle and then extended up to get connection to the charging contacts (Figure 37**Error! Reference source not found.**). Since an autonomous hauler has an open bucket, installation of a pantograph on top of the vehicle is not possible. The application which has been already tested by Volvo on the smaller TA15 is an inverted pantograph that comes up from underneath the hauler (Figure 38).

Figure 37 Classical bus charging application using a pantograph.

Figure 38 Inverted pantograph charging solution for an autonomous hauler.

There are challenges with the pantograph solution in a mining and quarry context. Connection between the charging components requires very precise navigation and positioning and the surfaces are easily corroded or otherwise impacted by dirt and dust. This is therefore not the preferred solution for the TAXX.

6.3.15.2 *Conductive system ACD - Industrial robot solution*

There are several suppliers of industrial robots who have experimented with developing an ACD. They have tested robot movement, gripping and handling of charging connectors and cables, using a vision system to plug in the connector. The advantage of this solution is that a standard charger can be used, and no modification on the machine is needed. Another advantage is that the ACD and the charger are two separate systems, which can also be debugged separately. Since the robot is not physically connected to the charging plug, in principle this system could be used to handle multiple charging cables and serve multiple machines simultaneously. This solution has not yet been implemented, so there is no performance data available. Industrial robots are in use globally in a variety of processes and environments, and robots are available for many kinds of environments or conditions, though they are usually adapted to indoor environments. The puzzle pieces are available, but the integration, testing and validation must be done by Volvo to create a complete automated charging solution.

- Should be able to easily handle MCS cable and connector weights.
- Potential to serve multiple machines with one robot system.
- Environmental protection comes from enclosures. While mating standard IP21 applies for the charging connector and inlet.

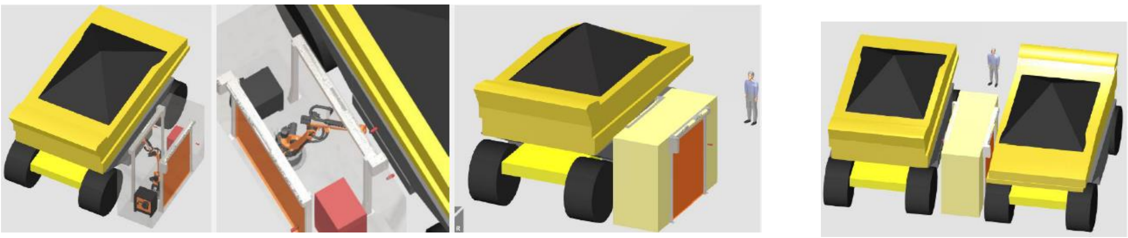


Figure 39 Concept model of an industrial robot charging system. Two TA60 could be served simultaneously (rightmost picture).

6.3.15.3 Conductive system ACD - Simplified robot charger

In the market there are robotic systems to plug in a standard charging plug, such as Type 1 or 2 connectors or CCS combo connectors. They are vision-based solutions together with a robotic actuator that can move in any direction and angle (six degree-of-freedom, see Figure 40). In normal operation, the charging cable is fixed to the robotic actuator, so one robot charger would be needed per charging station. Many of the same advantages and disadvantages as for the industrial robot solution, but because a simpler movement system is used, cost will be lower than the industrial robots

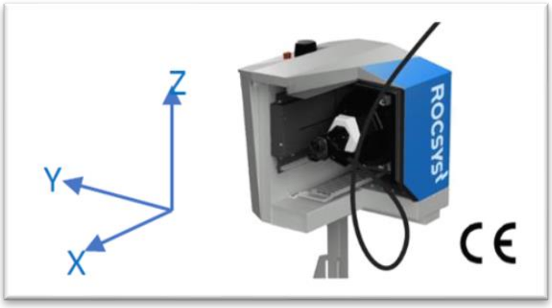


Figure 40 Example of a simplified robotic ACD. This is a 3D model by Rocsys company.

In principle, standard charging connectors and inlets have an IP21 rating, but the system manufacturers can offer extra packages to allow protection of the charging connector while idle. The TAXX could also include a solution to protect the vehicle inlet, for example with a movable hatch and environmental sealing. While mating, the charging contact will always have IP21. The maturity of these add-ons, however, is quite low. We have not identified any installation in a more heavy-duty and harsh application. Finally, the charging connectors for manual charging are not intrinsically made for automated connection, and there exist questions about wear and tear in harsh environments such as quarries or mines.

- Environmentally sensitive during mating.
- Less costly than industrial robot solution.
- No support for MCS-weight cables and connectors (yet)

6.3.15.4 Conductive system ACD - Charging pin solution

Figure 41 Example of a pin-and-socket ACD, in this case QCC system by Stäubli. Shown is the actuator and vehicle socket with funnel.

There is also a conductive charging solution based on a pin-and-socket connection. The advantage is robustness and environmental resistance. The pin is somewhat flexible and has a pivoting base. In combination with a funnel at the socket opening, the system can take care of misalignment between the pin and the socket using mechanical freedom, and the pin is guided into the socket by the funnel (Figure 41). The contacts on the pin are also shielded by a shroud. Once inside the vehicle-mounted socket, the pin extends out of the shroud, and the contacts contact to the socket-side, after which charging can commence, further enhancing robustness. Because the contacts are shielded continually, while idle as well as during the mating process (with IP55 minimum), this pin-and-socket solution has already found use in some industrial settings, such as ports, where it has seen reliable operation over multiple years.

- The technology is available off-the-shelf.
- (Environmental) robustness is much higher than for manual charging connectors.
- The vehicle-side socket is larger than a regular charging inlet.

6.3.15.5 Conductive system - Charging station and infrastructure

For every ACD discussed in the sections above, there needs to be a charging station to supply the power. For conductive charging, there are many suppliers that provide charging stations up to 350 kW of power, using the standardized connectors, such as the CCS combo connectors, GB/T, or ChaDeMo. Any charger following these standards in the region and fulfilling the power and communication requirements can be used. Some manufacturers are also working on realizing charging stations that comply with a future higher-power charging standard, known as MCS (Megawatt Charging System), initially aiming for 700 kW of charging power. MCS specifies charging powers up to 3.75 MW should be possible using the same physical connector in the future.

6.3.15.6 Wireless (inductive) charging system

In the last years, wireless charging systems have been increasingly promoted for automotive industry, both in stationary applications, when a vehicle is charged on a parking spot, and dynamic application where a vehicle can charge while driving (Figure 42). We have investigated using a wireless charging system for the TAXX. Having charging pads mounted on the outside of the vehicle, exposed to the rough environment, is a challenge. The system also requires an inductive charger that delivers high frequency current to the charging pads, to generate magnetic fields that can be transferred to the vehicle receivers. The wireless system's advantage over a conductive system is that there are no moving parts, which keeps maintenance to a minimum. Testing and evaluation is still ongoing, and the system shows good results and promising future. The maturity of these systems has not yet been proven for autonomous hauler applications. The power level is limited, and it is not known if it is able to reach power levels of 1 MW, which may be needed for the TAXX in certain applications. Currently the price of inductive systems is high, but looking on market situation and increasing interest, it seems likely that more systems will be deployed in the coming years. At that time, they may be of interest to the TAXX, but inductive charging systems are not currently prioritized.

Figure 42 Examples of inductive charging solutions

6.3.16 Dynamic charging

Dynamic charging means that the machine can charge while it is moving. The power transfer can be conductive using a rail or catenary with a suitable current collector, or wirelessly through induction (Figure 43). Dynamic charging is of interest to provide extra energy when travelling loaded uphill, or when travelling long distances on fixed roads between, for example, a loading and unloading spot.

Figure 43 Example of a dynamic charging system (Trolley assist) on rigid dump truck

Dynamic charging technology could drastically reduce the time the machine stands still to charge, or even eliminate stand-still due to charging, which increases machine productivity. Additionally, the haulers would need to cover less distance on battery power alone, so the battery size on the machine could be reduced as well. On the other hand, a dynamic charging system requires more infrastructure which is spread out along the haul route, driving cost. Whether a dynamic charging system is worth it or not, is ultimately based on comparing the cost of the infrastructure to the increase in productivity and savings on the total machine fleet, which will have to be done for each specific site based on its circumstances.

For the TAXX, the dynamic charging pantograph must be mounted either in the bottom part of the vehicle or on the side, which differs from current charging systems. Therefore, we can expect even higher cost of infrastructure to provide the necessary voltage.

After a high level study of the wireless charging concept, we conclude that this system is not sufficiently viable to be prioritized in the short term.

6.3.17 Productivity simulations and machine models

The purpose of the TAXX machine is to transport material from one location to another. Therefore, estimation of the cycle time and productivity is of great interest. By considering all sequences of a load cycle as illustrated in Figure 44, the cycle time, productivity and the energy consumed on one cycle can be estimated. The output is also used to evaluate the tires with respect to excessive wear, which is a risk if the load on the tire in combination with velocity is too high.

The simulations with the described 1D-model only represent the performance of one single machine. To simulate a fleet of machines on a site, with potential bottlenecks causing standstill or impact of fleet charging strategies, requires discrete event simulations. This was managed by BTH in work package H4 (see section 6.6.4).

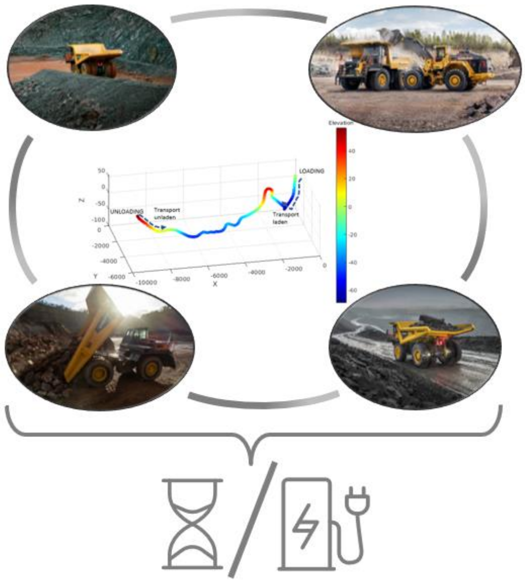


Figure 44 Illustration of a load cycle.

To simulate a site with a fleet of TAXX, the following machine characteristics were shared between Volvo and BTH:

- Weight information and axle load distribution
- Max velocity
- Max traction force
- Battery energy and power capacity
- Target State-Of-Charge (SOC) window
- Charging power
- Driveline efficiency
- Dump time
- Estimated times for positioning machine when loading, unloading and charging.

Unlike the features or models used to evaluate the design components, these are the ones that represent the final vehicle design after relevant choices were made and that were deemed to be relevant for the site and fleet simulation.

6.4 H2 - OPEN PIT MINE DIGITALIZATION

6.4.1 Purpose and Scope

This section provides the deliverable as defined in the Aspect project application for work package H2. Drivers and contributors of work package H2 including this report are ERICSSON and TELIA.

6.4.2 Terminology and Abbreviations

3GPP	3rd Generation Partnership Project
A-GNSS	Assisted GNSS
APN	Access Point Name (4G)
DNN	Data Network Name (5G)
DSCP	Differentiated Services Code Point
eMBB	Enhanced Mobile Broadband
GNSS	Global Navigation Satellite System
IoT	Internet of Things
LTE	Long-term Evolution
NR	New Radio (5G)
PTT	Push-to-Talk
QoE	Quality of Experience
QoS	Quality of Service
RTK-GNSS	Real-time kinematic positioning
TCU	Telematic Control Unit
ToD	Teleoperated Driving
URLLC	Ultra-Reliable Low Latency Communication
VRU	Vulnerable Road User
WP	Work Package

6.4.3 Summary

The digitalized Open Pit Mine benefits from 5G communication and several network features allowing it to operate in an efficient manner.

The digital services and associated communication characteristics that shall be provided on a digitalized site range from low volume and high latency to high volume and low latency specifications. Different vehicles’ services but also different services on a single vehicle can have a range of data flows with unique characteristics needs. The 5G network can accommodate these requirements through applying slicing and quality of service to maintain an optimal service, even with a challenging site topology.

The dimensioning of the 5G network needs to be balanced against the teleoperated driving and other digitalization technology needs on the site, so the efficiency of the site remains in focus. The communication density is heavily impacted by the number of connected mining vehicles in a single location, and by the chosen teleoperated driving technology for each vehicle.

Network features like positioning and exposure enable and enhance the advanced services that are required, like Site Management, Fleet Management, Production Management and Digital Twins. Emergency Stop and Teleoperated Driving are key examples of functions requiring these network features.

An Open Pit Mine that has been digitalized with connected machines and tools may be exposed to cybersecurity threats that needs to be considered. Secure and reliable frameworks are in place for the 5G infrastructure in the public telecom operator domain. To mitigate cyber threats in an Open Pit Mine with private 5G communication infrastructure, a similar approach adopted to enterprise needs must be applied.

A digitalized Open Pit Mine requires easy and efficient operation; at the same time the criticality of network performance is crucial to avoid disturbances in the enterprise production. Support services for the network are needed to meet requirements of service continuity and optimize efficiency of operations to secure network KPI monitoring.

The majority of the required network features can be provided today through standardized 5G network functions, that are commercially available. A subset is also already available in 4G allowing support for a wider range of devices.

Through the 5G network a Digital Twin gains access to a range of data signals from the connected digital site, allowing for continuous optimization of the production efficiency and energy usage.

An overview of the key objectives and deliverables for work package H2 are provided in Table 8 and Table 9. An overview of findings is presented in the next sections.

Table 8 Key objectives for work package H2.

Key objectives	**Status**
Identify requirements and develop a system architecture for the digital infrastructure for ASPECT.	Completed.
Validate the digital infrastructure.	Completed.

Table 9 Deliverables for work package H2.

Deliverable	**Status**
Define and document the digital infrastructure architecture to support use cases for electrified autonomous systems.	Completed.
Reference model and documentation of the system solution.	Completed.
Demonstration on a test site of information flows to/from vehicles through the digital infrastructure.	Completed.
Functional verification of telematic functions – remote operation, monitoring.	Completed.
Adaptation and operation of digital infrastructure during the project.	Completed.
Final report and conclusions.	Completed.
Business models to support the industry’s needs to automate and electrify fleets.	Completed.
Operational support and solutions focusing on private networks but long-term enabling the public network to manage electrified transport solution.	Completed.

Reference material to use in future projects.	Completed.

6.4.4 Introduction

The digital infrastructure required for, in this case, an Open Pit Mine operation, consists of a number of components, when looking at the architecture from a data flow perspective (Figure 45).

Digitalization of the site will involve introducing connectivity to a variety of objects which in turn will improve the overall utility, efficiency, and productivity of the mining operation.

The objects to be connected can be divided into passive items that will report sensor information, and control objects which report sensor information and require a control data stream. The sensor objects data flows can range from simple temperature readings to high-definition video feeds. The control objects data flows range from signals to open a gate to full teleoperated driving data flows.

The 5G private network will handle each of the data flows according to the required priority and timing, to provide the highest communication efficiency.

The Control Tower represents the set of functions required to operate the site and manage the production. It relies on both on- and off-site cloud services from several actors providing production and site services.

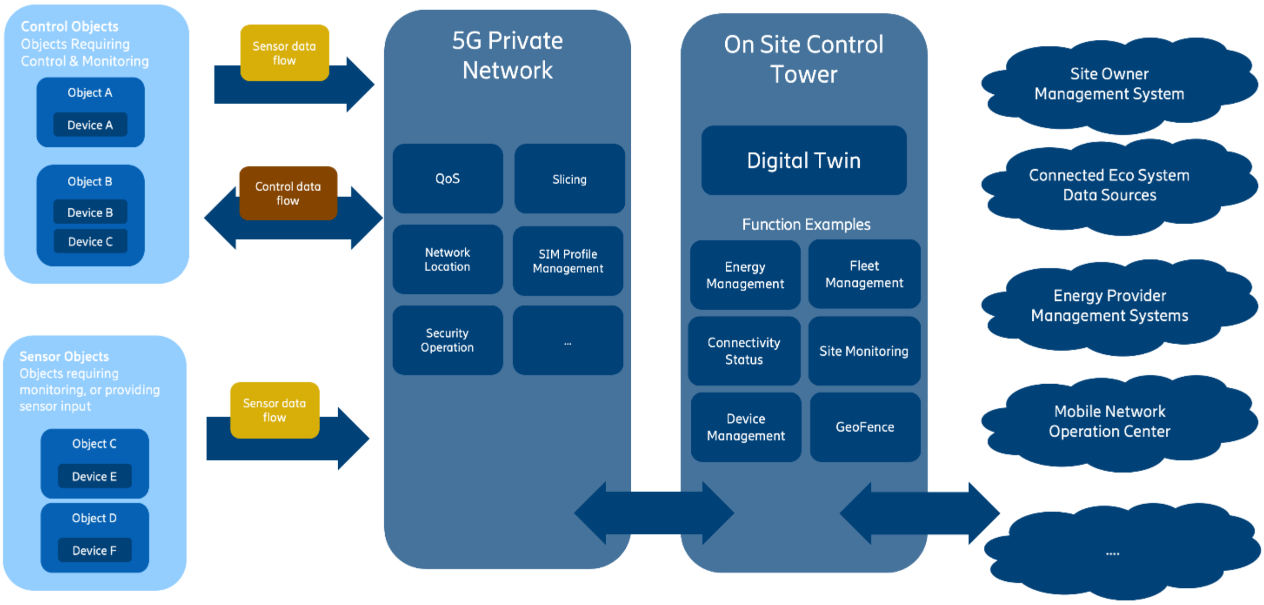


Figure 45 5G Cellular Network on a Digitalized Site

6.4.5 Open Pit Mine Communication Characteristics

The characteristics of a typical open pit mine and its associated mining processes are used as a guiding example to identify the main communication requirements.

The general production process is either a form of quarrying, where blasted rock itself is the product or a form of open pit mining, where minerals are to be extracted from some of the rock. With respect to the communication the processes can be considered similar.

The following facts can be outlined that will impact the communication architecture and design.

The **topology of the site** impacts the **cellular coverage** needs as does the device distribution on the site:

The crushed material is transported from one or more pits, which are often lower than the surrounding area, to a secondary crusher at ground level, after which it is transported to a logistics point. Both the secondary crushing location and the logistics location can be located some kilometers away and may require passage through tunnels.

The pit has roads (benches) on the side of the steep pit walls that lead to the bottom of the mine. These pit walls will require good coverage, so electric haulers can remain connected and be teleoperated in the case of unforeseen circumstances.

The roads have one- and two-way areas, which may be divided into different sections for fleet supervision. Currently only one vehicle may reside in one section at a time, but this may change with improved fleet management. This implies that there is a relatively even distribution of vehicles over the transport area of the site.

The geometry of the mined area will change over time as material is mined, implying that the cellular coverage may have to be adjusted occasionally which puts higher requirements on the mobility of cellular radio masts.

Centrally in the deep pits more vehicles and machines are operated, increasing the **communication density**:

Drill rigs are used to break down the blasted rock.

Blasted rock is loaded into a **pre-crusher** by an **excavator** in the pit.

Conveyor belts transport the crushed material away from the pre-crusher.

The crushed material in the pit is loaded onto the **electric hauler** with a **wheel loader.** Two vehicles interacting with each other, where one or more are autonomous is a **high-risk** process, that requires increased monitoring, especially when human drivers are involved.

The drill rig, excavator and wheel loader can be operated by a person or be **remotely operated.**

The electric haulers can operate **autonomously** but can also be **operated remotely**. The transition from autonomous to teleoperated driving (ToD) mode is a critical process that needs careful supervision, shall preferably take place under motion, and requires reliable coverage.

There are also other aspects of the mining process that impact the required communication characteristics such as reliability, availability, and latency:

For electrification efficiency many **electric haulers** are required, to allow for a **continuous flow of material**. This creates a production dependency chain, similar to a manufacturing production line, thus putting higher demands on the connectivity robustness to avoid a production stop.

Emergency stop functionality, which is integrated in vehicles and in machines, and available through explicit emergency stop buttons located around the site, requires reliable and latency sensitive connectivity to support the heartbeat and emergency control signaling.

Finally, the whole production process must be monitored, which can be enhanced through the 5G network:

All actors in the mine will require **location tracking**, i.e. people, machines and trucks, rely on GNSS, A-GNSS, RTK GNSS or other positioning technologies. Dead reckoning or other non-GNSS positioning solutions are required when GNSS coverage is not possible in tunnels when transporting material to the logistics point.

6.4.6 Device Categories on Site

The various vehicles, machines, and infrastructure elements as well as personnel use one or more communication devices to facilitate the production and site operations. Several categories of devices need to be supported, where each device instance needs to support one or more data flow types.

- **Integrated TCU in electric haulers with <u>one or more modems:</u>**
  The minimum requirement on an electric site is to connect the electric haulers, which have integrated TCUs for supervision, and may use the same or additional modems for Teleoperated Driving (ToD).
- **Integrated TCUs in wheel loaders, excavators, and drill rigs**:
  These machines are supervised and may have ToD capabilities.
- **Integrated modem in conveyor belts and crushers**:
  The conveyor belts and crushers require supervision
- **Integrated modem in charging station**:
  The changing station needs to be monitored to collect usage data for optimization of the production and detect failures.
- **Location Tracking Device:**
  Vulnerable Road Users (VRUs) e.g. guests, will carry devices for location tracking.
- **Push To Talk Device:**
  Workers and operators in- and outside of vehicles will have Push-To-Talk (PTT) devices for communication. These may be combined with the Location Tracking.
- **Emergency Stop Device**:
  Physical emergency stop buttons are located at various points around the mining site.
- **Security Cameras**:
  The site will have video coverage of most areas.
- **Site IoT Devices**:
  A number of other sensor types are used around the site for e.g. measuring the road and weather conditions, monitoring the state of gates, and state of charging stations.
- Other:
  Smartphones (Private/Business/Guests) will be present on site, but these are typically handled by the surrounding public network.

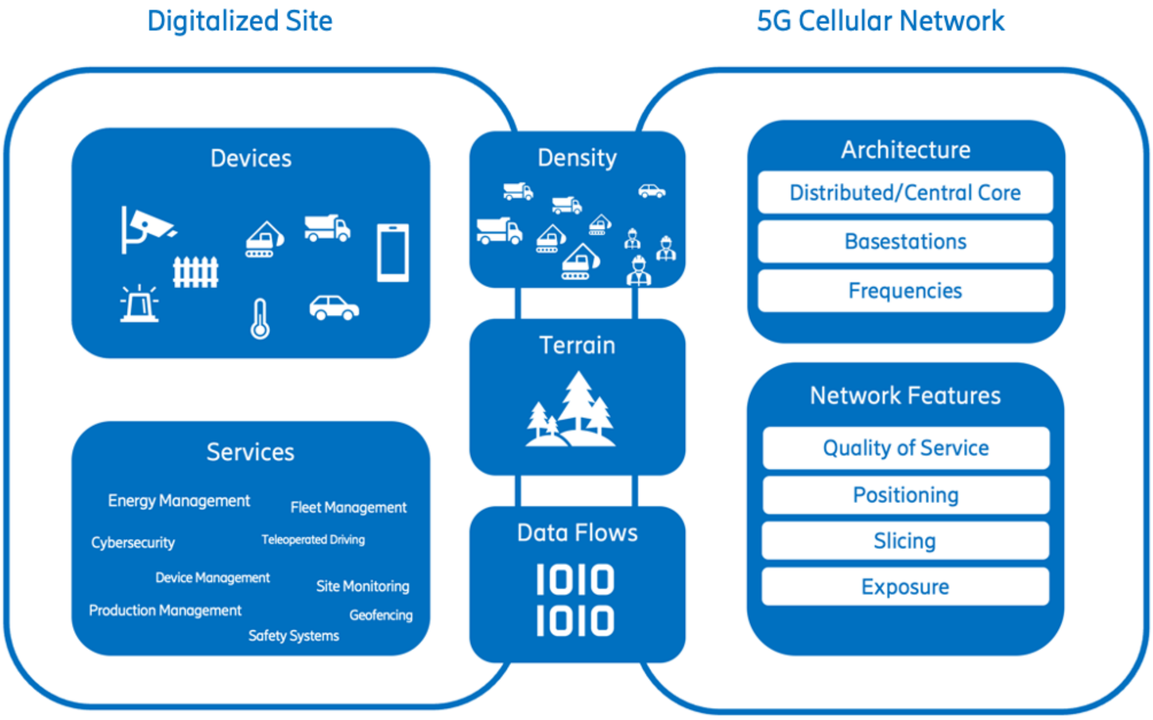


Figure 46 5G Cellular Network on a Digitalized Site

6.4.7 5G Network Characteristics

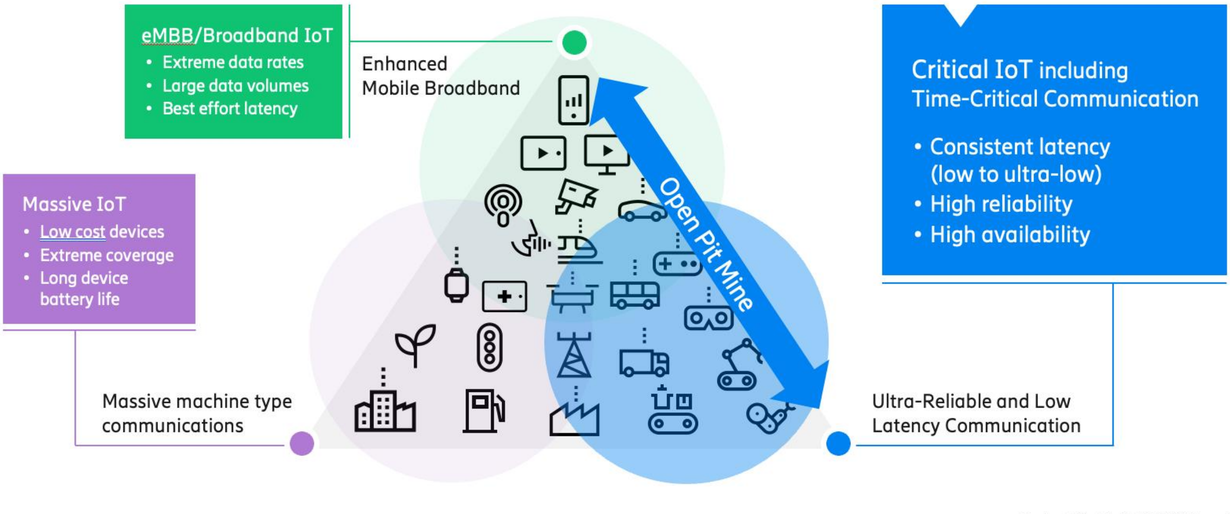
The required 5G network setup is defined by the communication use cases on the site. The requirements for these use cases can be split into the non-functional characteristics such as bandwidth, latency, and reliability of the communication, versus functions that are required for e.g. positioning, device provisioning, monitoring and information exposure.

The non-functional characteristics can be refined per device type and per data flow that is needed to support the device dependent use cases. Additionally, the device density on the site determines the scale at which the data flows are loading the network in the different areas of the mine.

6.4.7.1 Data Flow Characteristics

Devices and their associated data flows shall be treated with the appropriate priority by the cellular network to ensure that the related services provide the expected Quality of Experience (QoE). These services have availability and reliability requirements that impact the target architecture and preferred configuration of the cellular network.

The devices and data flows can be categorized into a few distinct communication types for the open pit mine, which are mostly in the range of Enhanced MBB to Ultra-Reliable and Low Latency Communication as outlined in the illustration below (Figure 47)



Based on: ITU's vision for IMT 2020 & beyond

Figure 47 Outline of different communication types

The main difference between the time critical communication and Broadband IoT is the reliance on data being delivered with a specific, deterministic, latency as outlined in Figure 47.

Time critical services require data packets to arrive below a hard upper latency limit with a specific reliability (Figure 48).

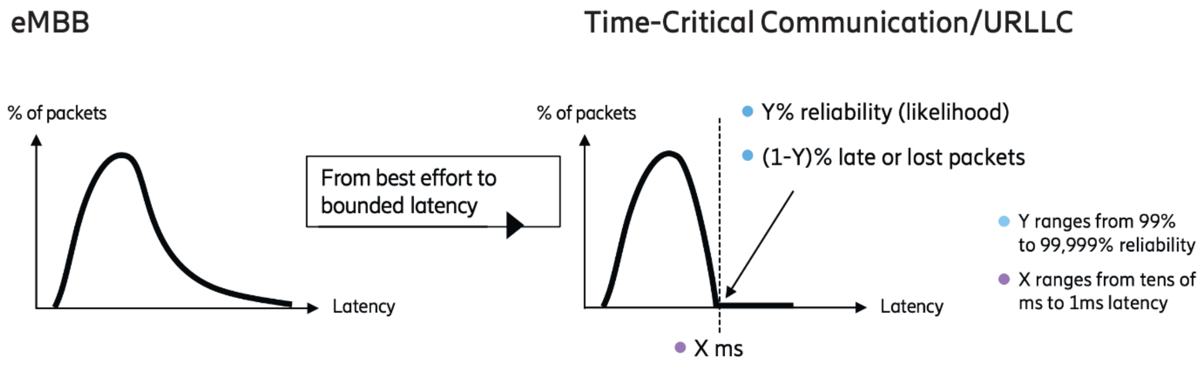


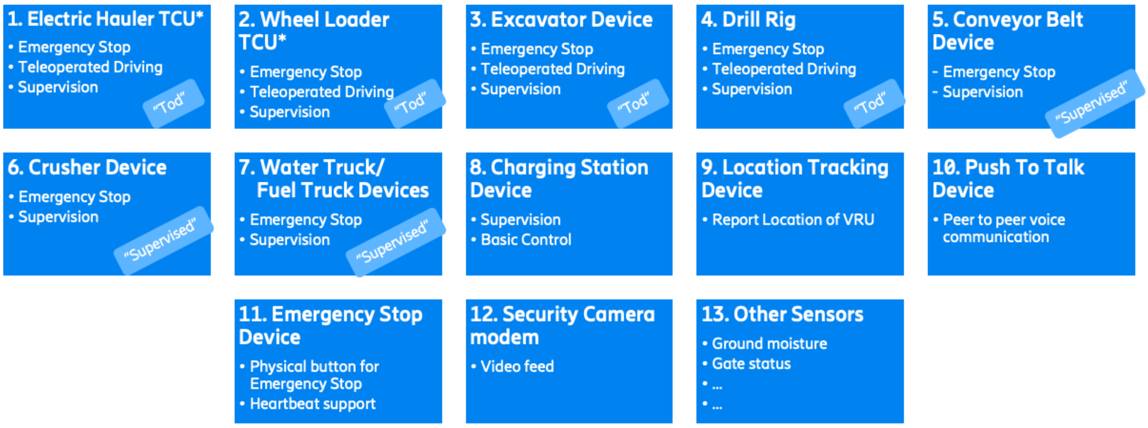
Figure 48 Time-Critical communication and bounded latency

The 3 main data flow categories that can be identified based on the devices used in the open pit mine are:

1. Critical IoT characterized by Ultra Reliable Low Latency Communication (URLLC)
   This category is time critical and requires low bounded latency but has limited bandwidth. This traffic shall have the highest priority in the network.
2. Critical IoT characterized by Reliable Low Latency Communication
   This category requires reliable low latency, and higher bandwidth.
3. Enhanced MBB
   This is a general category where bandwidth requirements can be high, but latency is not time critical.

Each of these data flow categories can be supported by the cellular network through Quality-of-Service profiles which are named as P1, P2 and P3 respectively in this document.

During production the devices must support a number of services, which are outlined in the diagram below, and which can be mapped to the 3 profiles.



*Multiple ECUs or modems may be used on a single vehicle

Figure 49 Device types used on a digitalized open pit mine site

The emergency stop service, which has low bandwidth and time critical requirements, requires the ultra-reliable and low latency category. The teleoperated driving service is less time critical, and has higher bandwidth requirements, thus requires the reliable low latency support category. The remaining services such as supervision and location reporting can be handled by the enhanced mobile broadband category.

In periods when the vehicles and other devices are not active in the production, maintenance related data related to software updates, telematics and system logs is exchanged. This maintenance data is best served by the Enhanced MBB category.

	QoS Profile		
Device Type	P1	P2	P3
Integrated TCU in electric haulers, wheel loaders, excavators, and drill rigs (1,2,3,4)	X	X	X
Integrated modem in conveyor belts, crushers, water- and fuel-trucks (5,6,7)	X		X
Integrated modem in charging station (8)			X
Location Tracking Device (9)			X
Push To Talk Device (10)			X
Emergency Stop Device (11)	X		
Security Cameras (12)			X
Site IoT Devices (13)			X

Figure 50 Device types and required QoS Profiles

The three QoS profiles need to support the data flow characteristics outlined in Figure 51, which are based on the requirements for the Emergency Stop communication, Teleoperated Driving communication, and typical Enhanced Mobile Broadband communication for a single teleoperated vehicle. These profiles can be assigned statically on a per device basis, when only a single QoS profile needs to be

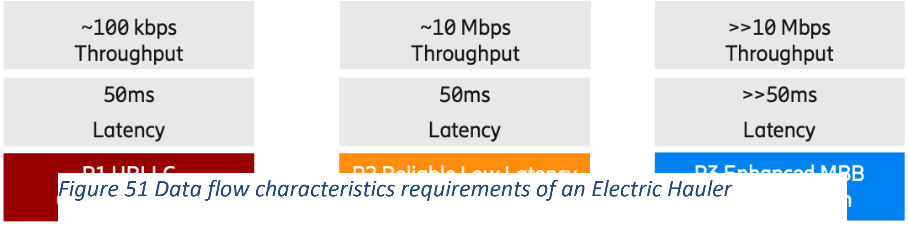


Figure 51 Data flow characteristics requirements of an Electric Hauler

applied. When multiple profiles need to be applied different solutions can be leveraged, which depend on the ability of the service to identify itself to the network. Typical solutions include using individual connections to the network (APN/DNN) for each service, or using another differentiation solution within a single connection, such as DSCP marking and/or IP addresses and port identification. If a more flexible approach is required, external exposure interfaces can also be used to assign the needed priority to the different flows and their dynamic network identities.

In Figure 52 the three QoS profiles are illustrated for the Electric Hauler, based on the categorization in Figure 50 and typical values required for these services.

The P1 profile is used for the Emergency Stop communication, which has very low data volumes, and requires reliable heartbeat signaling below 50ms. This will have the highest priority in the network.

The P2 profile is used for the Teleoperated Driving communication, which consists of downlink signaling and uplink video data. This will have the highest priority in the network besides the Emergency Stop communication. The uplink video part of the profile will be flexible to accommodate a balanced throughput among all the remote-controlled vehicles. Besides using a specific priority, L4S can also be added to the profile for superior video performance, and efficient usage of the available spectrum.

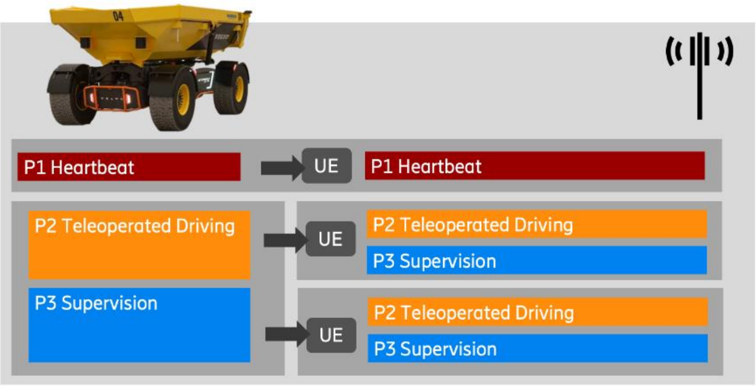


Figure 52 Example of how QoS flows could be used with redundant or dedicated UEs

The P3 Enhanced MBB Communication profile does not require high throughput for the teleoperated vehicle during production work. However, when in maintenance mode, software updates and log uploads will use higher throughputs while the vehicle is stationary. This will have the lowest priority so there is low risk of affecting the other two QoS categories.

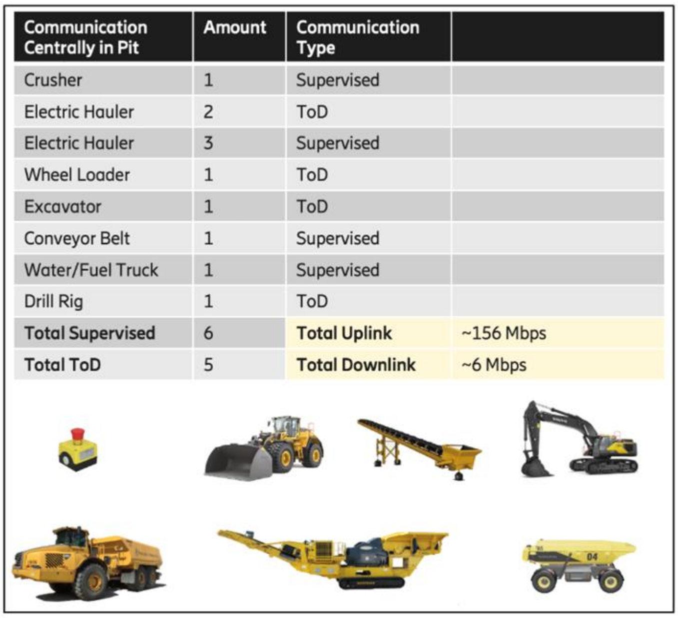
When using a single device, it is still important to have effective flow control e.g. TCP or other control mechanisms that leverage L4S.

The Electric hauler can apply the QoS Profiles in several ways as previously described, using one or more modems. In the example above the emergency stop communication has a dedicated modem with a P1 QoS profile. The Teleoperated Driving and Supervision services use two redundant modems, each with a P2 and P3 QoS profile, to increase reliability.

6.4.7.2 *Communication Density*

Besides the data flow requirements, the total number of devices actively communicating on the site defines the required cell coverage and related capacity. The site requires full coverage, but the required capacity may differ in particular locations depending on the device density.

An open pit mine will require a significant number of electric haulers to fulfill the production needs and require substantial communication bandwidth when in teleoperated driving mode. The number of haulers simultaneously in teleoperated mode is expected to be 1 or 2 at most.



Communication Centrally in Pit	Amount	Communication Type	
Crusher	1	Supervised	
Electric Hauler	2	ToD	
Electric Hauler	3	Supervised	
Wheel Loader	1	ToD	
Excavator	1	ToD	
Conveyor Belt	1	Supervised	
Water/Fuel Truck	1	Supervised	
Drill Rig	1	ToD	
Total Supervised	6	**Total Uplink**	~156 Mbps
Total ToD	5	**Total Downlink**	~6 Mbps

Figure 53 Example of future communication for connected machines in the digitalized open pit mine.

In the center of the pits additional machines may be teleoperated in the future, which shall be taken into consideration when planning the network capacity. Figure 53 shows an example of a future scenario with 5 teleoperated machines and a number of other actors in a central location of the mine, of which the communication needs can be accommodated with 5G cellular network technology today. Note that the Electric Haulers will typically run in autonomous mode, meaning the communication density in the example is considered exceptional.

The communication in general is dominated by uplink data flows during production hours, whereas both uplink and downlink data flows are heavily used when the vehicles are parked for maintenance and charging.

To optimize solutions for sustainability and evolve digitalization, the communication solutions for teleoperated driving shall be balanced against the required cellular communication footprint. As 5G communication evolves, more machines, and more advanced digitalized solutions can be leveraged, leading to more efficient communication utilization.

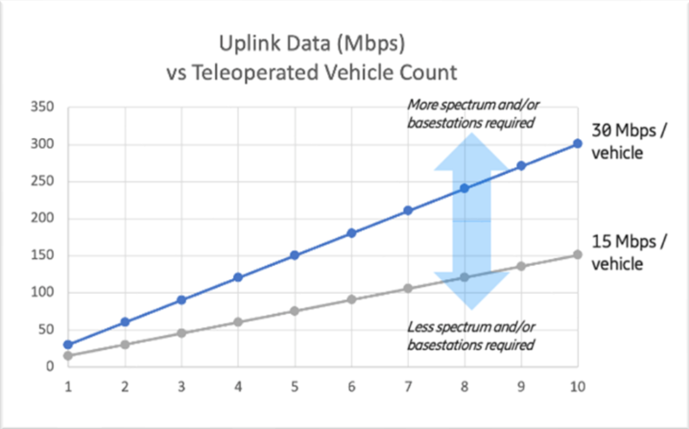


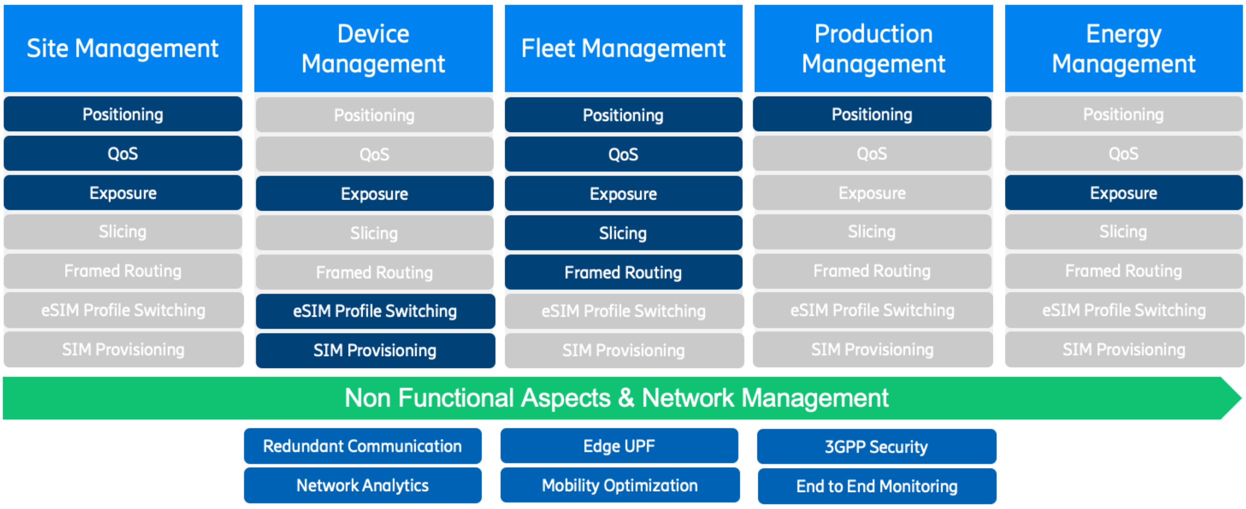
Figure 54 ToD solution impacts the cellular network requirements.

6.4.8 5G Network Features Supporting the Digitalized Site

The data flow categories and the communication density set the basis for the approximate dimensioning of the private network. The first network feature that has been discussed is QoS, which will ensure that the different data flow types meet the expected data flow characteristics.

Besides supporting the basic communication needs there are other site needs that must be supported through the network, and the related Control Tower (Figure 55).

- Network Management
    - SLA Monitoring
    - Cybersecurity
- Site Management
    - Safety & Security
    - Emergency Stop
    - VRU Protection
    - Geofencing
- Device Management
    - Device Onboarding and Provisioning
    - Network Switching
- Fleet Management
    - Teleoperated Driving
    - Emergency Stop
    - Supervision
- Energy Management
    - Energy Usage Monitoring
- Production Management
    - Coordination of Production Machines



Site Management	Device Management	Fleet Management	Production Management	Energy Management
Positioning	Positioning	**Positioning**	**Positioning**	Positioning
QoS	QoS	**QoS**	QoS	QoS
Exposure	**Exposure**	**Exposure**	Exposure	**Exposure**
Slicing	Slicing	**Slicing**	Slicing	Slicing
Framed Routing	Framed Routing	**Framed Routing**	Framed Routing	Framed Routing
eSIM Profile Switching	**eSIM Profile Switching**	eSIM Profile Switching	eSIM Profile Switching	eSIM Profile Switching
SIM Provisioning	**SIM Provisioning**	SIM Provisioning	SIM Provisioning	SIM Provisioning

Non Functional Aspects & Network Management

Redundant Communication	Edge UPF	3GPP Security
Network Analytics	Mobility Optimization	End to End Monitoring

Figure 55 5G Cellular Network Features

Positioning

Network location functions can provide the needed location information to the Control Tower, which in turn mediates this to cloud services through geofencing and publishing logic.

QoS & Slicing

The identified data flows benefit from dedicated treatment by the network, using the discussed QoS profiles. This enables optimized usage of the network which in turn enables the required premium services. Note that Low Latency Low Loss (L4S) can also be used as part of the QoS setup to improve streaming video.

Primarily demanding services benefit from the QoS feature, but this does require all data for all services to be categorized accordingly to achieve the desired experience.

Device Provisioning

Machines, vehicles, and sensors need to be provisioned in the network in the most efficient manner possible. Basic onboarding and management are available through network O&M functionality.

On a digitalized site, this provisioning process shall have close interworking with the cloud services, such as Fleet, Energy and Site Management to achieve efficient device onboarding and management.

Network Switching (eSIM Profile Switching)

The transition from the public area to the open pit mining site is challenging for connected vehicles and equipment. Solutions for switching between networks can support the flexibility required when a machine or equipment must be moved between two mining sites, or when materials need to be transported between sites.

Networks Behind Device

Digitalization of the open pit mine drives the needs for more connectivity between all cloud services and all the machines involved in the production process. The machines themselves have multiple processes that are integrated towards the cloud services and may require network separation. Providing transparency to local networks on a machine behind a communication device, allows even more diverse communication solutions.

Network Exposure

Control Tower services can access the cellular network for monitoring purposes including location, connection and analytics data. Control is also possible for more dynamic cases, such as changing the QoS settings temporarily or setting application server details related to QoS, when the application determines the QoS needs, rather than the preconfigured SIM.

Non-Functional Characteristics

Predictable and Reliable Communication, SLA Monitoring and Cybersecurity are required to fulfill the Service KPIs and associated SLAs.

Redundant communication, Edge UPF, Mobility Optimization and 3GPP Security will enhance the service. Network Analytics and End to End Monitoring will provide the needed insights into the level of SLA fulfillment.

Cybersecurity

A digitalized Open Pit Mine has high demands on data security for the operational use and to meet stringent requirements on functional safety. Reliable connectivity for information flows must thus include protection from cyber-attacks. The open pit mine assets with a risk of exposure to cyber-attacks include:

- Information assets: the data in transit, the user data, the control signaling, the network management data, the data stored in data centers
- Infrastructure assets: systems, platforms, and applications

Threat actors include organized cyber criminals, nation states, hacktivists, terrorists and insiders. These attackers are generally motivated by three main targets: Money by ransom blackmail, stealing of business sensitive information and data or sabotage. Security weaknesses that could be exploited are:

- Security policy not enforced or monitored
- Lack of hardening, and insecure configuration of the network
- Operational procedures
- Lack of visibility, control, and monitoring

Cybersecurity solutions require collaboration between actors and understanding of the system and data flows not only between automated equipment but also to sensors, site operations centers and control towers for remote management and teleoperations. To define efficient mitigations for the cybersecurity threats on Open Pit Mines, threat modelling is key.

Already system planning should follow the “secure by design” principle. Efficient end-to-end security control on the Open Pit Mine infrastructure should be realized through continuous vulnerability assessments and applied mitigation solutions on the components/systems at risk.

Maintaining end-to-end security is a complex task. Thus, the mitigations should address the following perspectives:

- How to protect the Open Pit mine network infrastructure from the outside?
- How to protect the Open Pit Mine infrastructure from users?
- How to protect users from users?
- How to ensure safety?

Compliance to global security standards is key to achieve the high confidentiality, integrity, availability and privacy requirements for an Open Pit Mine critical infrastructure.

Standardization forms the base for mobile network security, ensuring interoperability and openness. Building on this base, many other aspects come into play: it’s when all the pieces come together in an orchestrated manner that we get adequate security throughout the mobile network.

For mission critical communication networks, the full end-to-end approach must be taken to mitigate security threats. Misconfigured devices or insecure settings may allow hackers to gain a toehold of the network, from which they can move laterally, infiltrate valuable data and establish command and control channels. Devices used in the Open Pit Mine increases the attack surface. Therefore, every time a new device is added to the network, it must be provisioned by a set of standards and processes, secured, and managed.

Based on intelligent and automated technologies, complete end-to-end solutions are critical for detecting, monitoring, and managing threats using real-time risk visibility and automated resolutions – delivering robust security from device to cloud.

Operation

Today, an increasing number of massive-data devices are connecting to the network and generating more value than ever for enterprise. In this new data-driven reality, it’s business-critical that network operations are performed at scale, with speed and in real time. In a complex world of massive data and millisecond latency a Network Management system serves, secures and scales opportunities in tomorrow’s enterprise and beyond.

Network management has become one of the key generators of business value in a connected solution, such as an Open Pit Mine. For today’s communication service providers, it serves as a critical tool to drive growth, improve customer experience and optimize infrastructure operations for optimal production.

Network management solutions include performance management, provisioning, security monitoring and mitigation, and support functions for network infrastructure energy management. Efficient optimization of the operations can be achieved through remote- and automated functions.

6.4.9 Conclusions and next steps

The 5G SA cellular network can provide the needed communication for the digitalized site today, when leveraging the available 5G network features including slicing, QoS, exposure and positioning. By taking a holistic view of all services related to the site the communication services can be provided in the most efficient manner. This report highlights the connected vehicle's communication characteristics and the required 5G network coverage, which can be extrapolated to the remaining on-site services. Future studies should focus on optimization of resource utilization through intelligent automated orchestration and enhanced functionality in the area of positioning and mobility through the 5G network to achieve effective, sustainable and cost efficient 5G communication and services.

6.5 H3A METHOD AND REQ. MGMT. FOR INFRASTRUCTURE AND STANDARDIZATION

6.5.1 Introduction to requirements management for the autonomous transport solution

An autonomous electric transport solution has many stakeholders that have needs and requirements for the system and solution. The functionality within the system itself is the most obvious- that it can execute the necessary tasks for transporting material. However, there are also needs and requirements to enable the development of the solution and verification and validation of the system. There are also site-specific needs in terms of infrastructure for mobile connectivity, safety systems and loading equipment. These components are a part of the autonomous transport system, but each site will require adaptation and configuration according to its context. Once the system is deployed, there will be a need to monitor and maintain the system to ensure the system performance over time. The focus for work package H3a has been to identify a method for requirements management of the site-specific needs and requirements (Figure 56).

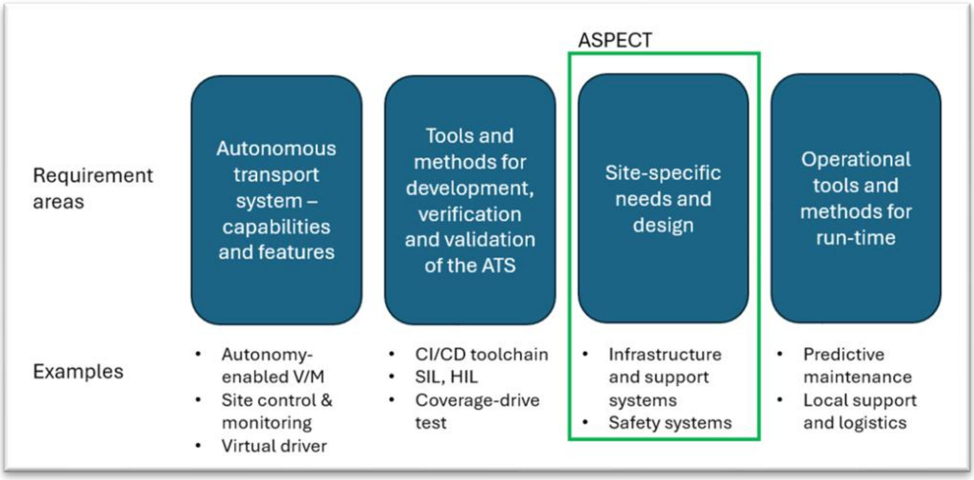


Figure 56 Illustration of areas for needs and requirements for the ATS in a confined area. The ASPECT scope is highlighted in green.

The deliverables for work package H3a are listed in Table 10.

Table 10 Deliverables for work package H3a.

Deliverable	**Status**
Define a method to identify and evaluate non-functional and functional requirements to enable a digital infrastructure to support the electrified and connected transport system in a confined area.	Completed.
Demonstrate the method.	Completed. The method has been applied successfully within V.A.S. for (confidential) customers and sites outside of ASPECT.

6.5.2 Overview of findings

When identifying the requirements needed for infrastructure and standardized implementation of the autonomous transport solution in a site, we must assume that there exists a minimum viable electric autonomous transport system with which to initiate commercial activities for the right customer and/or site. As we scale and expand the customer base, features and services will be added to the autonomous transport system (ATS).

When we discussed the electric autonomous transport system with prospective customers within the mining and quarry industry, it became clear that there was a relatively standardized set of questions or topics that needed to be investigated for each site. The answers then formed the basis for a design and planned configuration of the site, processes and implementation of the ATS, as well as identification of gaps and potential showstoppers relative the initial available functionality of the ATS.

The basic concept for an open pit mine or a quarry is the following:

- Material (rock) is blasted into smaller pieces in one or more locations in a mine or quarry.
- The material is loaded onto a transporting vehicle or machine through some loading equipment.
- The material is transported to an unloading location and unloaded.
- The transporting vehicle/machine returns to the loading site to complete the load cycle.

Additionally, the following is valid for most mines and quarries:

- Most machines and vehicles are diesel-based.
- There is little or no connectivity in terms of 4G, 5G or wi-fi.
- Communication is mainly done by radio (walkie-talkie).
- Electricity is mainly available at the “main office” or near any other electrical equipment such as a crusher.

We have identified several topics to be discussed with the customer, when considering the implementation of the ATS. Table 11 provides the context of current operations and allows us to evaluate the feasibility of implementation of the ATS. Questions related to power supply and charging stations are only relevant for electric machines, but diesel-based trucks have similar questions in terms of fueling stations and procedures.

Table 11 Questions to evaluate feasibility of an ATS in a confined area based on as-is context.

Topic	Sub-topics
Applicable legislation for autonomous transport solutions in a mine or quarry	- Labor, safety and environment - Site operations permit - Product and service certification, e.g. CE marking in Europe

Current site operations	- Processes and way of working o Operations – overburden removal, drilling, blasting, loading, transporting, unloading o Hours of operation – 24x7, 9x5? o Road maintenance o Equipment maintenance & repairs o Safety o Business administration o Visitors & customers - Personnel, schedules and responsibilities - Control room location and procedures - Type of material transported – size, density - Loading method and equipment (silo, excavator, wheel loader, other) - Material weighing method - Unloading method and equipment (hopper-crusher, ground, other) - Integrations with site systems (traffic signals, operational data) - Productivity requirements over time
Physical conditions on site	- Temperature and temperature variations - Climate – dry, wet, foggy, windy - Dust and dirt - Haul routes – distances, elevation differences (loaded uphill or downhill?), road conditions and rolling resistance - Future expansion and layout (what ground is fixed, what will disappear over time?)
Electric equipment on site	- Power supply and limitations- size, location, cost to expand - Other electric consumers (crusher, dryer, etc.)
Connectivity and communication on site	- Internet connection - Mobile data connectivity (4G, 5G, wi-fi) and coverage - Radio frequencies used (walkie-talkies or other device communication) - Wireless TCP/IP communication
GNSS	- Location of site (latitude) - Position of benches and pits vs satellite locations (“shadows”)

In Table 12 we summarize several topics that need to be discussed to define the autonomous transport solution as it will be implemented in a site, with all supporting processes and infrastructure. These provide input to the specific configuration of the support infrastructure and the design and configuration of the ATS. The scope for ASPECT was restricted to a confined area above ground.

Table 12 Questions to identify design, configuration and implementation of the ATS in a confined area.

Topic	**Sub-topics**
Confined area and autonomous operating zone (AOZ)	- Level of confined area that is required. - Hours of operation for the autonomous transport solution, as defined by loading and unloading methods and equipment - Boundaries and methods to restrict access to the AOZ during operation - Need for personnel or equipment to enter or exit AOZ during operation (e.g. pauses, shift change for manual vehicle operators, drilling on other benches)
Parking	- If not 24x7, where to store vehicles/machines when not in operation - Charging options during stand-still
Maintenance & repairs	- Procedure to manage breakdown, repairs or maintenance of an autonomous vehicle/machine- on site or other

	- Road maintenance during autonomous operation
High power charging solution	- Optimal placement of charger(s) - Distance from power supply (TRAFO)
Location and management of ATS site control & monitoring server and personnel	- Placement of control room and site operator
Communication requirements	Non-TCP/IP - Vehicle navigation and sensoring - Walkie-talkie - Video surveillance (wired) Wireless TCP/IP: - Communication between vehicle and control tower– maps, missions, requests for keys, status updates, data logging, video transmission - eStop: top priority in network - Teleoperation – control of vehicle, video feeds from vehicle - Voice communication - Video surveillance (non-wired) - Communication with gates, other safety measures - Other connected devices: security vests, office equipment, other production equipment and vehicles, other streaming media, Office365
Safety	- Safety case and procedures - Safety measures – barriers, emergency stop triggers, fences - Emergency stop - Video surveillance - Other types of surveillance
GNSS	If needed, measure GNSS coverage and signal strength on site. Management of GNSS-denied areas (localization/navigation).
GDPR and GDPR-like contexts	Management of personal data as captured by the autonomous transport solution during operation (Lidar, Video, safety driver, other)
New roles & responsibilities	Changes in roles and responsibilities for some of the personnel on site – what options are there in terms of technical skills and interest in new tech?
Implementation activities	How can implementation of the ATS be done in parallel with ongoing operations?

The autonomous transport solution for a site is designed based on the answers to these questions. This includes defining the boundaries of the autonomous operating zone (AOZ), security measures to keep the boundaries and trigger emergency stop if the boundary is broken, haul routes and lane definitions, location of charging station(s), loading and unloading areas and procedures, routines for entering and exiting the AOZ or pausing operation, etc. We must understand if there are GNSS-denied areas so that Lidar-based navigation is required and ensure that the 5G-network coverage is sufficient across all relevant areas of the site for the required functions, as described in chapter 6.4. The details of how to operate the site within and outside the AOZ must be planned and documented, so that the logistical flows are optimized to minimize waste and inefficiencies in terms of transport downtimes. Examples of activities that must be planned and managed:

- Drilling and blasting while autonomous transport on existing benches is ongoing.
- Pauses (e.g., toilet visits, food pauses) for personnel operating within the AOZ, such as the loading operator.

- Breakdown of a machine within the AOZ.

The ATS requires changing some of the ways of working in a site and it is imperative that all planning be done together with the site owner, site operator and personnel. The scope within ASPECT has been a Confined area level 2 (CA2) which means that interaction between autonomous and non-autonomous vehicles can be done at low speed. It also means that personnel can be in the autonomous operating zone (AOZ) during operation if properly shielded by a certified vehicle or other barriers. The mining segment requires a higher CA-level where autonomous and manual vehicles can interact at higher speeds. This places higher demands on the autonomous solution and the safety mechanisms on the base vehicle/machine itself, whereas for CA2, certain safety requirements are primarily handled by careful management of the activities allowed in the AOZ and introducing safety procedures for the personnel. Therefore, when the ATS is deployed at higher Confined Area levels, the requirements on the different sub-systems and the ATS as a whole increase.

As mentioned previously, site infrastructure is a key consideration for an energy optimized site, but the questions can be simplified in the short term.

- Is there enough available power at the site to support the charging of autonomous vehicles, based on the maximum number of simultaneous chargers and expected charging patterns?
    - If not, what is the cost for increasing the power supply?
    - Is there any other way of distributing the power across all consumers, without impacting productivity?
- What is the cost for connecting to the internet with sufficient bandwidth and speed?
- What dimension of private 5G is needed for the site in question, and what is the cost for implementing the 5G infrastructure?

If the infrastructure cannot be secured, then the electric autonomous transport solution cannot be implemented. A key challenge is therefore to identify the right customers and sites to begin the industrialization and scaling of the electric autonomous transport solution, since the initial investment costs can be significant and long-term partnerships are required. This is similar to the long-term piloting and implementation of autonomous diesel-based transport solutions for Komatsu and Caterpillar at various larger mining sites, with the added complexity of electrification.

The long-term vision of the energy-optimized site, with interoperable autonomous and manual electric vehicles and machines, is farther in the future. Planning and replanning operations at a site, based on current energy prices and available power, requires advanced AI and machine learning, as well as more mature solutions. There is no stakeholder interest in investing in such advanced energy optimization. We must start with the basics and what we can control at each level, as the electric and autonomous solutions mature.

There are of course differences between a small rural quarry and a giant, modern mining site, but the basic concept is the same. The challenge of electrification and autonomous transport solutions is therefore not only one of the machines or the solution itself, but the available infrastructure on site and the initial cost of bringing the relevant infrastructure up to the required standard. Given the rural location of many mines and quarries, electrification and mobile connectivity will require significant investments, which might make or break the business case for autonomous electrified transport solution.

In the next chapter, Göteborg University presents its findings for requirement engineering for digital twins and AI.

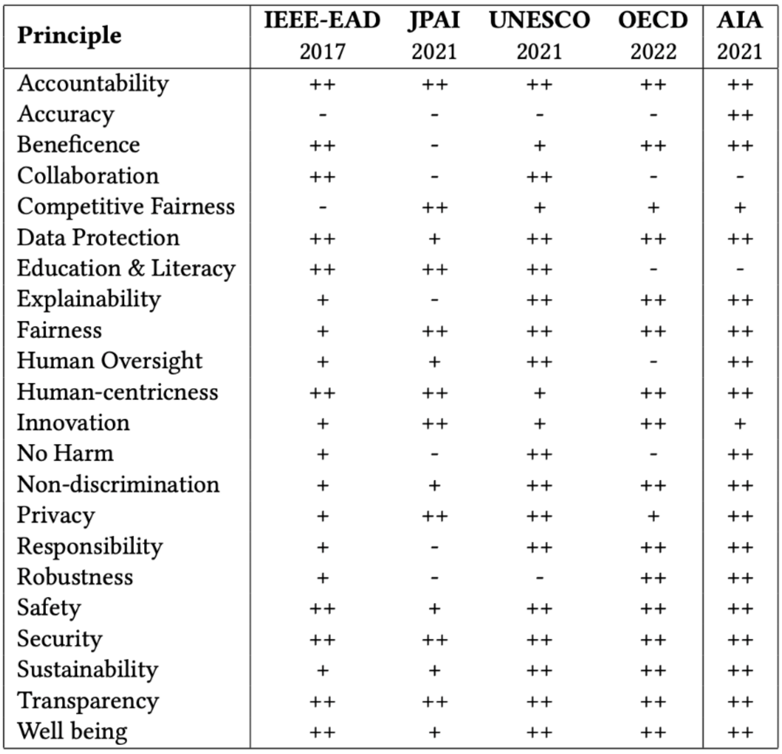
6.6 H3B REQUIREMENTS ENGINEERING FOR DT AND AI

6.6.1 Requirements Engineering for Digital Twins

The research conducted by the team at Göteborg University (GU) offers insights into the methods for eliciting requirements for a digital platform to monitor a real mining site with autonomous vehicles.

The papers mentioned can be found in 7.2 Publications.

The envisioned system requires gathering real time operational data, while the nature of the vehicles driving within the site, even if at low speeds, could pose a threat to the safety of bystanders. As per the current European Union regulations, all systems that could pose a threat to the safety or security of humans should comply with a number of high-level requirements. These requirements are studied in detail in Paper D, as well as compared to the requirements recommended by different authorities, as seen in the table below. In turn, Papers B and C focus on human oversight requirements and the role of Digital Twins (DTs) in monitoring the mining site from the point of view of safety, security, and auditability.



Principle	IEEE-EAD 2017	JPAI 2021	UNESCO 2021	OECD 2022	AIA 2021
Accountability	++	++	++	++	++
Accuracy	-	-	-	-	++
Beneficence	++	-	+	++	++
Collaboration	++	-	++	-	-
Competitive Fairness	-	++	+	+	+
Data Protection	++	+	++	++	++
Education & Literacy	++	++	++	-	-
Explainability	+	-	++	++	++
Fairness	+	++	++	++	++
Human Oversight	+	+	++	-	++
Human-centricness	++	++	+	++	++
Innovation	+	++	+	++	+
No Harm	+	-	++	-	++
Non-discrimination	+	+	++	++	++
Privacy	+	++	++	+	++
Responsibility	+	-	++	++	++
Robustness	+	-	-	++	++
Safety	++	+	++	++	++
Security	++	++	++	++	++
Sustainability	+	+	++	++	++
Transparency	++	++	++	++	++
Well being	++	+	++	++	++

Paper A also connects DT development to the high-level requirements imposed by the EU, but instead focuses on the reusability of the components that make up a DT. To explore this topic, an exploratory case study was conducted, interviewing experts in both industrial and academic contexts. The literature on DTs was reviewed to prepare the interviews, that were then recorded, transcribed, anonymized, and analyzed in accordance with a well-known thematic analysis guideline, as reported in Paper A.

These interviews highlighted a number of challenges in DT development, including poor practices in requirements engineering, the use-specific nature of DT systems that lack common standardization, or the overall complexity of DTs that requires industry-specific solutions. Furthermore, many participants highlighted the necessity for quality tools in requirements engineering to bridge the understanding gap between mechanical engineers and software developers.

Taken together, papers A, B, C, and D inform the Requirements Engineering (RE) processes for DTs.

6.6.2 Method for requirements elicitation for Digital Twins

Even though no specific requirement elicitation method for DTs exists in the literature, there are many works that propose methods to elicit requirements, identify dependencies (very relevant for DTs), gather company-specific mandatory requirements and relevant regulatory policies, specify data requirements, etc. However, DTs are complex systems that are difficult to analyze and elicit requirements for.

Therefore, we first aimed to clarify what characteristics of DTs make it difficult to elicit requirements. In order to address this question, we conducted interviews and attended meetings to understand the challenges in requirements elicitation for DTs. In the first round of interviews, we attempted to understand the roles and needs of different partners in terms of scope, starting point, priorities, etc. Based on the insights provided by the experts, a number of iterations were conducted in order to design an artefact that could be used to elicit requirements for DTs. In each of these iterations, the method was presented and analyzed by the partners and their suggestions were integrated in the artefact. Below, we present a set of questions that could effectively guide the functional and non-functional requirements elicitation tasks for a DT of a real open mining site.

In our project, we found that the general use cases of DTs were not always clear for all parties, due to the complex set of possible uses, in order to captures use cases, along with stakeholders, goals, and long-term plans, the following questions can be asked:

- Which stakeholders (internal and external) to the company will use the digital twin? For example: engineers, managers, customers, auditors, etc.
- What are the uses cases for each stakeholder? For example, real-time monitoring, optimization of efficiency, etc.
- Do any of the stakeholders have particular goals when using digital twins? For example, to have a shared understanding of a site, to save energy, etc.
- How to priorities use cases and which ones matter the most currently (to focus on)? How would this be decided? How to focus on a sub-set of use cases?

The answers to these questions can be used to map the stakeholder and use cases to specific goals or long term plans. Then, a second set of questions can help us focus on a few concrete scenarios to illustrate operation and design. To start, it is helpful to focus on standard, every day operational scenarios, e.g., an autonomous vehicle driving to a harbor. The questions are:

- For the digital twin in question, what are the main operational scenarios of concern? There should be at least one, describe them with a short name.
- Are the main operational scenarios of concern the same for all stakeholders, or do they vary per stakeholder?
- For the main scenarios, what operating assumptions are made?
- For the main scenarios, are there particular modes of operations that are relevant to explore, that is, certain changes to the context or assumptions which may affect operations? For example, teleoperation.

- For the main scenarios, are there particular edge cases that are relevant to explore, that is, situations within the scenarios which are potentially unusual, problematic, or may stress the system? Examples could be extreme weather or network disruptions.

In some cases, DTs might be subject to the same regulations or software development standards than their physical counterpart, especially if they are safety critical systems. Examples of such regulations are the Euro 7 emissions standards, ISO 26262, or the Off-Highway Construction Equipment Regulations. To identify the relevant regulations for the DT, and to connect those to mandatory requirements, we should ask the question of "Are there mandatory requirements, for example those imposed by standard, regulations, or internal company policies that apply?"

Then, the following questions are to guide the systematic identification of data sources and drive the conversation with relevant stakeholders and manage the expectations:

- What type of data is needed to facilitate digital twin operation?
- What duration should the required data capture? For example, for an hour, for a day, for a month, for a year, etc.
- What frequency of recording should the data cover? For example, near continuous, once per second, once per minute, once per hour, etc.
- How often should the data be updated to update the digital twin? For example, real-time updates, daily updates, monthly updates, etc.
- What format should the data be in? For example, spreadsheets, JSONs, etc.
- Who owns the data and who can provide the data?
- What concerns about privacy and ownership are associated with the data?

However, other questions, specific to the domain of the DT in question, might need to be added. For instance, additional questions on the data sources could be:

- What are the key data variables associated with each use case?
- From what data source does the variable come from?

Each combination of the identified use cases and data sources should be considered to extract one or more key variables of interest for the analysis.

Finally, quality requirements can be systematically identified by asking "Considering the digital twin operation from the perspective of the stakeholders, main use cases, edge cases, and data sources, what are desirable quality requirements?" We must add measurements to such quality requirements, e.g., for prediction, results must be accurate to some percentage, simulation results must be produced within some time, etc.

6.6.3 Requirements Engineering for Artificial Intelligence (GU)

On the other hand, studies have been conducted to address the question of whether Artificial Intelligence (AI) can help in Requirements Engineering (RE) processes, while considering the high-level recommendations highlighted in papers A, B, C, and D.

For instance, Paper E looks into requirements classification and tracing using Large Language Models (LLMs). These tasks are essential components of the RE process, involving the organization and tracking of requirements to ensure their successful implementation. By evaluating different prompt patterns for automating these tasks using GenAI, the paper aims to improve the efficiency and effectiveness of the RE process, thereby facilitating the elicitation of requirements for the digital platform designed to monitor a mining site with autonomous vehicles.

On the other hand, Paper G evaluates LLMs' performance for user story evaluation. User stories help prioritize features and communicate end-user needs within development teams, making them essential for effective requirements elicitation. This paper also highlights the importance of considering ethical and reliability aspects within the RE process.

In turn, Paper F looks into potential issues of using LLMs for RE tasks. The concepts proposed in the paper, such as defining "desirability" and identifying "prompt smells," could inform considerations regarding the reliability and effectiveness of using AI technologies for requirements elicitation in the RE processes, ensuring its trustworthiness. Taken together, papers E, F, and G study the role of AI for RE.

6.6.4 Conclusions

Like other complex cyber-physical systems, DTs need to be created with a number of requirements in mind. The method proposed by Göteborg University, that aims to help in systematically eliciting requirements for DTs, can allow practitioners to come up with an initial overview of what is required and that can later be used to adapt the requirements to changes. While Papers B, C, D, E, and F do not directly address Digital Twins, they each provide valuable insights that indirectly impact the development and implementation of DTs in various ways.

Moreover, the research conducted in the scope of the ASPECT project also addresses the question of whether AI can help in requirements elicitation and other RE processes. Paper G, for instance, explores the automation of requirements elicitation through the evaluation of user stories, utilizing ChatGPT to assess user story quality and offering insights into streamlining the requirements elicitation process. Similarly, Paper E discusses the automation of requirements engineering tasks, evaluating prompt patterns using GenAI to enhance requirements elicitation processes.

Further work, however, is needed to better understand the requirements for the proposed digitalized mining site. For instance, our research has shown that a modular microservice architecture is crucial for the developing reusable DTs. Other technologies, like data lakes, blockchain, or Internet-of-Things connectivity, are highlighted as essential for real-time interaction between digital and physical twins (e.g., a digitalized mining vehicle).

Future research could therefore look into combining these technologies and practices to create a holistic architecture and further refine it by adopting model-based systems engineering in RE. More concretely, our research could also be extended to include evaluations of the drafted architectural framework by domain experts, followed by a design science study to implement and test this architecture in a controlled industrial environment in which to deploy the digital platform to monitor the mining operations.

6.7 H4 – BTH DIGITAL TWIN, SITE MODELLING AND SIMULATION

6.7.1 Background

In the dynamic landscape of the construction and mining industry, integrating sustainable practices has become paramount while pursuing general improvements in efficiency, effectiveness, and safety in site operations (Lima et al., 2021). Autonomous electrical construction machines have drawn plenty of attention lately (Frank et al., 2019), with manufacturers exploring and demonstrating different designs, from the automated hauling systems proposed by (Caterpillar, 2021) and (Komatsu, 2023) to fully electric, autonomous transport solutions (Volvo Construction Equipment, 2021).

One of the major application areas for autonomous electrical equipment is transporting material in repetitive flows in confined off-road environments like quarries. Designing such solutions for maximum productivity, safety, and sustainability is not only a matter of optimizing the base vehicle. Equally important are design decisions concerning the support of operations, including charging stations, control towers, connected cloud solutions, and maintenance and repair support. Simply put, the size, range, and number of machines deployed on a construction site, as well as the number, capacity, and position of the respective charging stations, will heavily affect the haul cycle and, in turn, the target production/transport volumes, impacting productivity and profitability.

This move towards electrification and autonomy is shaking the construction industry's traditional working modes and design doctrines while creating a new range of opportunities by rethinking how these solutions are offered to the customers. Business propositions such as the "pay for autonomous transport capacity" - as proposed by (Volvo Autonomous Solutions, 2023) - are becoming popular to improve the value delivered to the customers while ensuring control over the system and leveraging profitability for the provider.

Designing these product service system solutions at an early stage requires careful analysis of several factors. Critical design decisions with regards to how the base vehicle, the infrastructure, the supporting services, and the controlling software shall be designed must be taken in the light of optimizing the system with respect to logistics flows, fleet and traffic management issues, machine efficiency, availability constraints, overall productivity and more. As discussed by (Hazrathosseini and Moradi Afrapoli, 2023), such a level of complexity in decision-making can only be tamed by investing in the digitalization of the construction sites and by the application of simulation support, the backbone of what is known as a Digital Twin (DT). DT can be useful not only in the build and operation phases of mining assets but also during its design phase. Applying a modular approach to creating these DTs provides further advantages, enabling the development of cost-efficient DT variants to be used for design space exploration (Panarotto et al., 2023). A modular approach enlarges the expandability of the DT system, boosting flexibility, scalability, and functionality, to support innovative services (Geng et al., 2022). A modular design supports better decision-making by allowing quick scenario simulations and by ensuring interoperability with existing systems. It improves simulation and analysis capabilities and allows easy customization and accessibility, even for non-experts.

In the multi-transition of diesel to electric, man-powered to autonomous, and product sales to transport-as-a-service, the need for an earlier and better understanding of design decisions' impact on operations and value creation is paramount. The project of ASPECT aims to work with this triple transition to support the ecosystem in creating better solutions for a more sustainable tomorrow.

6.7.2 Purpose, research questions and method

Our research work has focused on the design of a hauling solution – where 'solution' stands for "agreed level of machine availability and productivity of the site – for small to medium scale mines. Under such premises, the design space is huge, and several macro and micro decisions shall be taken to ensure maximum value for the customer. While it is essential to include aspects related to the physical equipment in the design decision-making activity, shaping such an autonomous and electrified transport solution means undertaking the development effort from a system-of-system (SoS) perspective. The latter shall address, for instance, aspects related to the optimal placement of various infrastructural components (e.g., chargers, parking areas, single vs double lane routes, etc.), considering different placements and configurations for the hauling routes (e.g., width, inclination, rolling resistance, etc.), the cost/effort to change the site setup, the placement of safety zone, and more. Furthermore, decision-makers should carefully consider the energy perspective of the site. Design support tools shall make it possible to conduct trade studies to identify the optimal State-of-Charge window for an equipment, as well as the optimal charging pattern to optimize battery lifetime & cost vs. productivity. These analyses shall also include other electrical machines on the site requiring charging and the behavior of other production machinery to manage power peaks by, for instance, including a battery energy storage system. Other variables to be considered by the Digital Twin are the available power from the grid, the cost of energy, the ability to connect solar or wind power based on the conditions of a site, as well as work schedules and the possibility of changing production schedules to spread power load. All in all, the number of perspectives required to capture and the width of the design space challenge the ways of designing and operating haulers in quarries, stressing the need for simulation support and a modular DT approach.

The work conducted in work package H4 has hence focused on developing a systematic approach to creating a modular DT structure for mining and quarrying operations, representing critical operational aspects such as productivity, energy consumption, emissions, and value creation. It serves as a versatile platform for simulating site performance under various operating conditions and machine configurations, including the number of machines, dimensions, and the use of fossil versus electric power. The primary objective of this modular approach is to facilitate rapid deployment and simulations across different customer operational settings, eliminating the need for extensive model-building efforts. This capability enables optimizing new system designs—encompassing product, service, infrastructure, and human interaction—in a digital decision support environment, known as the Decision Arena, before physical implementation. This approach offers significant development cost savings and adds value for end customers.

Based on this, a set of research questions has been derived:

- How can Digital Twins be developed and implemented to simulate new behaviors in new product-service systems and their impact on energy systems and the environment?
- How can the value-cost-sustainability trade-off of a new Product-Service System be quantified during the early design phase in the presence of multiple customer scenarios in a digital decision support environment?

This work package has utilized Action Research (AR) as the main methodological approach to achieve the previously stated purpose and answer the research question. AR uses theory and practice where problem identification, action interventions, and reflective learning are iterated among researchers and practitioners (Avison et al., 1999). It is a suitable approach when the research should take place in the studied context when a desire exists for active integration between descriptive and prescriptive actions, as well as when the research should be characterized by an active collaboration of practitioners (Bradbury, 2015). This makes AR a suitable approach since work package H4 requires active collaboration between partners and stakeholders.

More concretely, the research within work package H4 was conducted iteratively with multiple learning cycles. Each learning cycle identified core problems to be addressed, assessed, and developed appropriate simulation model/-s, and the intervention was evaluated. New issues or challenges were continuously identified, and as the knowledge of the problem domain increased, higher granularity and more complex solutions could be developed. The AR approach enabled a solution to be concurrently developed with building a knowledge foundation, ultimately leading to higher fidelity and usefulness of the final solution.

6.7.3 Objectives

A set of objectives or goals was determined in conjunction with the research questions. These can be stated as follows:

- Raise awareness of uncertainties and secondary effects linked to the transition to electromobility and autonomy in terms of aspects linked to product design, economics/business model, and environment.
- Create a set of generic replicable approaches for the simulation (e.g., discrete event, agent-based, system dynamics) of the transition towards electromobility and autonomy that can be implemented in new contexts within a reasonable time.
- Make scenario-based simulations of alternative system configurations available in minutes to assess strengths, weaknesses, threats, and opportunities for value creation and improvement of environmental performance at a site during decision-making meetings.
- Realize operational digital twin for real-time flows in an operational environment.
- Integrate information flows from the simulated environment to the operational digital environment.

6.7.4 Results and deliverables

The analysis of the literature available has shown that current DT applications in the mining and construction sector include mainly Site Monitoring, Manpower, Equipment, Asset and Supply Chain Management, and Safety analysis (Zhang et al., 2022). The study has also underlined that, in this domain, DTs are often merely regarded as highly matured versions of conventional simulators, e.g., (Hazrathosseini and Moradi Afrapoli, 2023). Among the most popular DT applications in the construction and mining industry, there are:

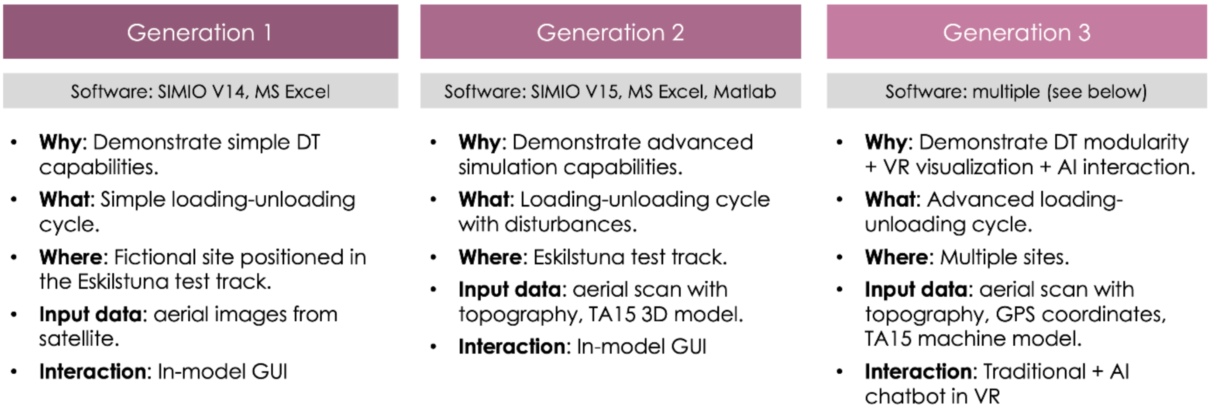
- PM (https://pmcorp.com) and Hexagon (https://hexagon.com/) offer simulation environments aimed at energy optimization of facilities. However, these solutions are not fully functioning digital twins, resulting in vague results with significant variations and poor precision.
- TIMining Aware (https://www.timining.com) is a digital twin of mine that provides visualization and situational awareness. It collects data from systems like Fleet Management, Drill Rig Navigation, and Processing Plant Control, integrates this data to create a real-time updated mine model, and enables remote visualization of the mine. Future capabilities include simulating operational scenarios for better decision-making.
- SymphonyAI (https://www.symphonyai.com) is a more general tool that is capable of building digital twins for specific processes, such as the loading and hauling process. It integrates various system data to create simulations and a comprehensive mine model, updating it in real-time for enhanced visualization and operational insight.
- MineLife (https://llamazoo.com/minelife/) merges geospatial and mine planning data into an interactive virtual replica of a mine site, accessible via desktop, VR headsets, and Microsoft Hololens. MineLife allows users to immerse themselves in the mine plan throughout its lifecycle, overlaying various data sets and infrastructure details. It facilitates easy access to information and high-resolution 3D visualization, and centralizes data for improved investor, government, and community relations, resource management, mine planning, and business development.

A common trait among the different applications is the underlying characteristic of passiveness. However, in dynamic environments such as mining, DT should be active with the aim of prediction and decision-making and should exploit the power of simulation to predict future events based on the already gathered data (Hazrathosseini and Moradi Afrapoli, 2023).

Furthermore, several recent papers have pointed to adopting a design-to-value approach concerning the development and implementation of DT in design (Javaid et al., 2023; Panarotto et al., 2023). The work conducted in the project revealed the different 'values' marketed by major providers of DT solutions, showing commonalities and differences in relation to the main benefits of adopting a DT approach when designing and operating complex solutions:

- Mevea (https://mevea.com) stresses the opportunity of delivering a 30% reduction in product development lead time, a 50% decrease in physical prototyping costs, and a 90% reduction in PLC software implementation time. DTs are marketed as solutions that remove barriers between departments, promote better product development with shared prototypes, and involve customers in the R&D process for valuable insights.
- Altair (https://altair.com) stresses the possibility of ensuring a seamless transition from concept to detailed design in mechatronic product development, enhancing early-stage design, analysis, and optimization, reducing prototype costs, and predicting real-world performance.
- Siemens (https://sv.siemens.com) emphasizes improvement in virtual validation of product performance as a main 'value' of DTs. Prototype costs, total development time, and product quality are the main KPIs lifted by the deployment of DT in design.
- IBM (https://ibm.com) stresses the possibility of providing insights for necessary product refinements before production.
- Dassault Systèmes (https://3ds.com) emphasizes sustainability as its primary value. The main selling point for DTs is to eliminate physical prototypes and provide safe environments for innovative green solutions, reducing waste and energy consumption products across their lifecycle.
- Autodesk (https://autodesk.com) spotlights the possibility of reducing the time spent updating models and minimizing decision-making risks.
- Makersite (https://makersite.io) stresses the possibility of making dependencies transparent and fosters collaboration, helping teams understand the impacts of design changes beyond their core expertise.
- Oracle (https://oracle.com) leverages the possibility of reducing development time and product costs, leading to more innovative and robust machine designs, as the main value of a DT solution in design.
- PTC (https://ptc.com) accelerates product innovation and reduces time to market. Their solution validates product performance early, minimizing costly late-stage redesigns.

Based on the results from the State-of-the-art and State-of-Practice, from the need-finding activities conducted with the partner companies in the project, and from the analysis of working documents, the work in H4 went through several iterations of the modeling concepts (aka, 'generations', see Figure 57) to eventually deliver a final conceptual framework for a modular DT.



Generation 1	Generation 2	Generation 3
Software: SIMIO V14, MS Excel	Software: SIMIO V15, MS Excel, Matlab	Software: multiple (see below)
• **Why**: Demonstrate simple DT capabilities. • **What**: Simple loading-unloading cycle. • **Where**: Fictional site positioned in the Eskilstuna test track. • **Input data**: aerial images from satellite. • **Interaction**: In-model GUI	• **Why**: Demonstrate advanced simulation capabilities. • **What**: Loading-unloading cycle with disturbances. • **Where**: Eskilstuna test track. • **Input data**: aerial scan with topography, TA15 3D model. • **Interaction**: In-model GUI	• **Why**: Demonstrate DT modularity + VR visualization + AI interaction. • **What**: Advanced loading-unloading cycle. • **Where**: Multiple sites. • **Input data**: aerial scan with topography, GPS coordinates, TA15 machine model. • **Interaction**: Traditional + AI chatbot in VR

Figure 57 Iterative generations through the course of this project.

The evolution of the different generations has focused on achieving the backbone simulation for the modular DT in alignment with the H4 objectives. The general architecture of the hybrid simulation platform for achieving these objectives is depicted in Figure 58. The architecture is generically built using a seamless connection between site and vehicle models. Such an architecture enables the combinatory use of agent-based or discrete-event modeling to accurately represent the SoS characteristics while allowing for a multi-fidelity simulation of individual system behaviors. This hybrid approach is recognized as a good strategy for reducing computational efforts while allowing for high granularity and accuracy (Shanthikumar and Sargent, 1983). The architecture directly links the site and vehicle models to enable quick interactions. At the same time, all other necessary operational data is stored in databases (in this case, either using Access or Excel) to facilitate data communication and storage. Finally, the collected data from the simulations are transformed, aggregated, and visualized to provide the user with an overview of the performance of one or several design options. The visualization includes a plotting and tabular presentation of value metrics and the capability for VR simulation of the site operation based on the selected operational scenario.

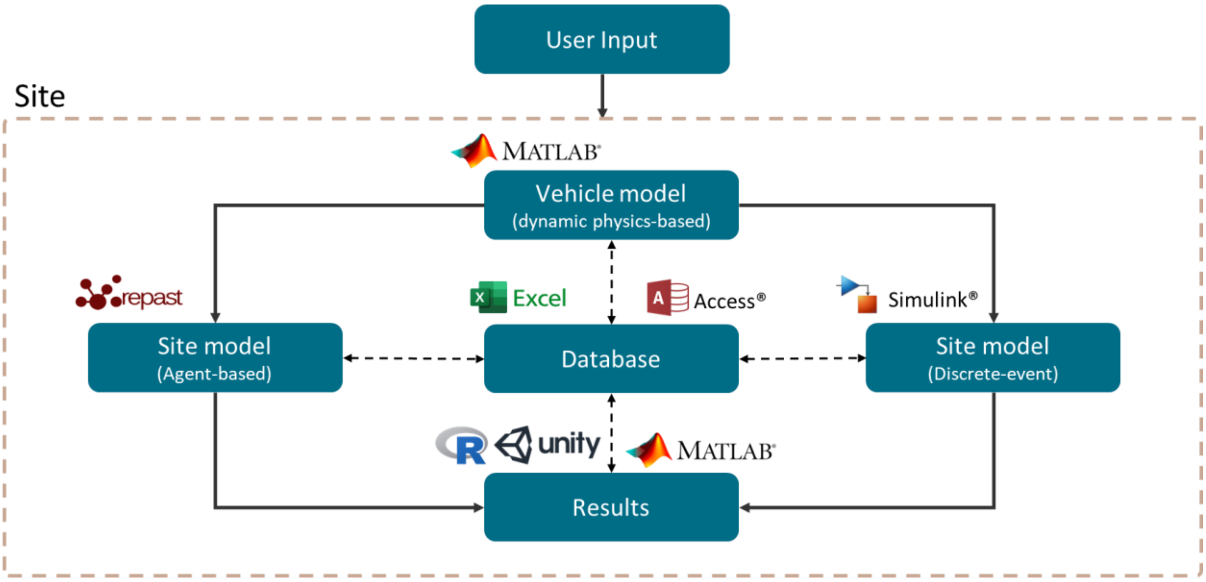


Figure 58 The architecture of the proposed hybrid simulation platform

The proposed simulation platform's architecture is flexible to tune it to produce the desired results. Thus, the site models have been developed using two different techniques: Agent-Based Simulation (ABS) and Discrete-Event-Simulation (DES). The two techniques build on two different perspectives for how to model a system or SoS. ABS represents a SoS by modeling agents with predetermined behavior that are then placed in a context over a given time frame. DES, however, models the process to be simulated and connects resources to the different process steps. In comparison, ABS can be seen as a decentralized modeling/bottom-up of a context, while DES is a centralized modeling/top-down (Borshchev and Filippov, 2004; Siebers et al., 2010). Depending on the aim and demand for granularity, either of the techniques can be used. ABS is better when a higher level of granularity and large demand for flexibility and temporal changeability are needed, while DES is more lightweight and better for lower levels of granularity where only the global metrics are sought (Hester and Tolk, 2010). Both approaches were included as the need might change depending on the user.

Figure 59 illustrates the key elements of the hybrid simulation platform utilized when using two different site simulation approaches: DES (on the left) and ABS (on the right). The grey boxes highlight the modules included in each approach. The DES-enabled approach is well-suited for platform optimization tasks (as shown in the grey box on the left). This is mainly because DES supports creating structured process models. While this rigidity can be a limitation for dynamically evolving sites, it becomes an advantage for platform optimization. DES can be exploited to test various system configurations along with their options to analyze the expected value. In contrast, ABS is better suited for exploring site value (as shown in the grey box on the right). ABS models individual entities (agents) with rules and logic, offering a much more flexible representation. This allows the user to simulate dynamic environments and uncover the interdependencies within different constitutive systems in the SoS. Also, such an approach is especially suitable for understanding the implications of choosing various operational strategies in conjunction with the SoS.

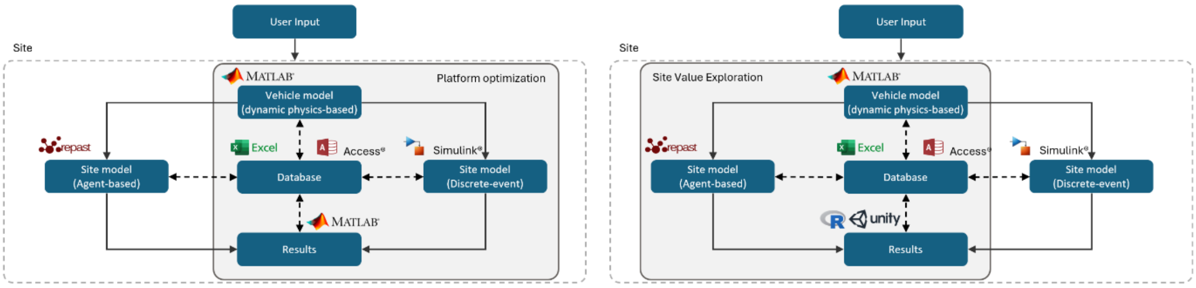


Figure 59 Key elements of the hybrid simulation platform utilized when using two different site simulation approaches, highlighted in grey boxes.

Both DES and ABS leverage a core modular vehicle model. This versatile model allows users to configure various vehicle types based on input. Users can define multiple vehicle configurations simultaneously to represent an SoS at the site. These configurations adhere to pre-defined constraints, ensuring realistic and suitable subsystem options for each system, i.e., the vehicle. Once a vehicle is configured, it is simulated in the context extracted from the operational scenario. There are two main types of vehicle simulation models: forward and backward. Backward models start at the wheels and calculate the total force needed to move the vehicle, working their way back to the engine. Conversely, forward models begin with the engine’s power output and distribute it to the wheels. Choosing a suitable model depends on the simulation goal. Forward models are better at simulating driver behavior and its impact on the system. Backward models are better at efficiently calculating energy consumption based on factors like vehicle weight and road conditions. They can quickly generate reliable energy profiles for different operational scenarios. A backward vehicle simulation model was chosen since the primary focus of the hybrid simulation platform was the value exploration of SoS. Once a model is built, there are three ways to analyze its performance, each offering a different level of accuracy (Guzzella and Sciarretta, 2007). First is the “average operating point” approach, which simplifies the entire drive cycle by averaging all operating states of the propulsion system into a single point. It provides a quick estimate of efficiency but lacks detail. Second is the “quasistatic” approach, where the drive cycle is divided into small segments, and factors like acceleration, incline, and vehicle weight are assumed constant. This offers more detail than the average point approach but doesn’t capture dynamic behavior. Third is the “dynamic” method that uses differential equations to model the complex dynamics of the propulsion system, generating highly accurate energy consumption profiles. However, it requires significantly more computational power. Thus, there’s a trade-off between accuracy and simulation speed. Choosing the appropriate method depends on the specific needs of your simulation. The quasistatic approach was chosen to balance the simulation accuracy and computational costs.

To simulate the vehicle using the models, dynamic programming (DP) was implemented. DP offers several advantages, mainly when dealing with complex problems. It is a structured way of breaking down complex problems into smaller, more manageable subproblems and constructing the solution to the overall problem using the subproblems. This ensures that the overall solution is indeed optimal by considering all possible combinations. Also, DP can leverage memorization and can be implemented deterministically or stochastically, depending on the problem and certainty of the system state transition. Besides, DP is applicable to various problems, including mixed-integer problems, seamlessly integrating discrete elements like gear changes with continuous variables like speed. Thus, DP served as a skeleton for various vehicle simulations that can be flexibly applied to electric and diesel machines. Once a viable vehicle is configured using several subsystems, DP is used to find an optimal velocity profile via optimal control policy. In this context, “optimal” refers to achieving a balance between energy consumption and time taken to complete the desired task. For instance, in the case of a hauler, the task might be transporting a payload from point A to point B. The “control policy” essentially defines a rule (or function) that dictates the vehicle’s decision-making based on the available information about its state (e.g., location, battery level, payload weight). The implementation details can be found in (Machchhar et al., 2024), published within the project, where a different prioritization to time vs. energy balance endured a different velocity and energy consumption profile for the given vehicle. Figure 60 exemplifies these differences on a short route, adapted from (Machchhar et al., 2024). The solid line represents the velocity profile when a higher priority is placed on time minimization, while the dashed line represents the velocity profile when a higher priority is placed on energy minimization.

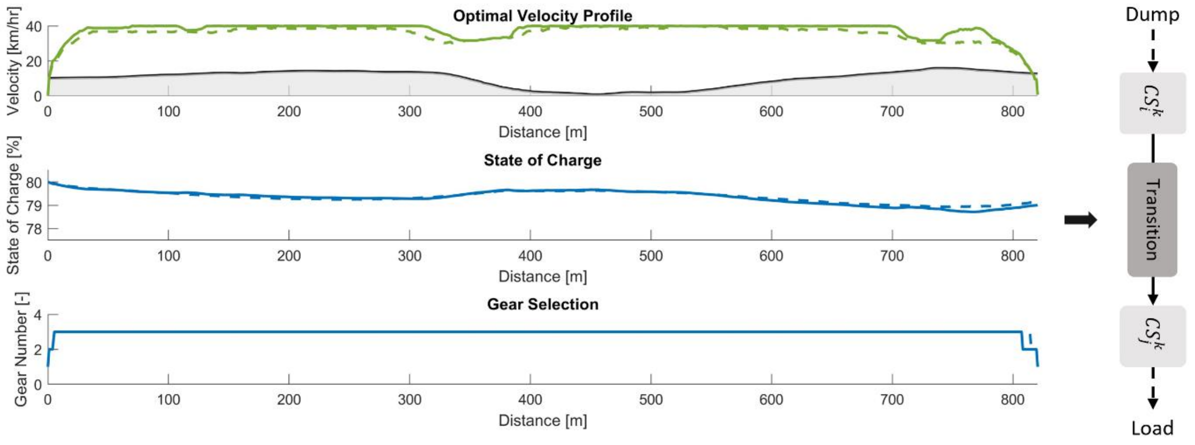


Figure 60 Different time vs. energy balance affecting the optimal velocity profile

There are two main approaches for advancing time in DES: next-event advancement and fixed-increment time advancement (Law, 2015). This mechanism, often referred to as the simulation clock, is a crucial aspect of DES, along with the list of future events scheduled to occur during the simulation run. When the advancement is set to the next-event, system state transitions are only allowed when an event occurs. The state of the system is assumed to be fixed in between. However, such an advancement technique enables long runs of operational scenarios, essentially enabling the assessment of the long-term value proposition of systems or subsystems. Figure 61 shows how the simulation results are fed to a DES representing an operational scenario. A constitutive system at i^{th} state transitions to j^{th} state, where time-aggregated results from adopting an operational strategy change its state. Several different SoS can be tested in an operational scenario to evaluate their overall value. As a result, the valuable design options to be a part of the solution platform can be identified based on the problem formulation and user-defined objectives, as exemplified in (Machchhar et al., 2024).

While this DES-enabled approach is well-suited for platform optimization, it falls short in developing a DT since it does not capture continuous processes or real-time changes, which are crucial for accurately reflecting the behavior of a physical system in a DT. Also, DES relies on pre-defined processes and rules, so it could be troublesome to model with dynamic systems that constantly evolve. DTs often need to adapt to changing conditions in the real world. Thus, the remainder of the results focus on the ABS approach as it is the most relevant for the work package H4 deliverables. A key advantage of ABS is that its building principle creates operational and managerial isolated agents (similar to the system's definition in SoS) that are then populated in an environmental context. This means ABS can mirror SoS, including its contextual, operational, and system boundaries. All in all, this gives the user great flexibility and scalability.

The developed ABS model was then integrated with the vehicle dynamics model so that haulers could obtain a hybrid simulation. From a practical standpoint, Figure 61 demonstrates how the simulation framework is set up and executed for a given design challenge. This figure is based on one of the papers (Toller Melén et al., 2024a) published within the project. The process targets a design sweep exploration, i.e., assessing all possible design and contextual configurations relevant to the site.

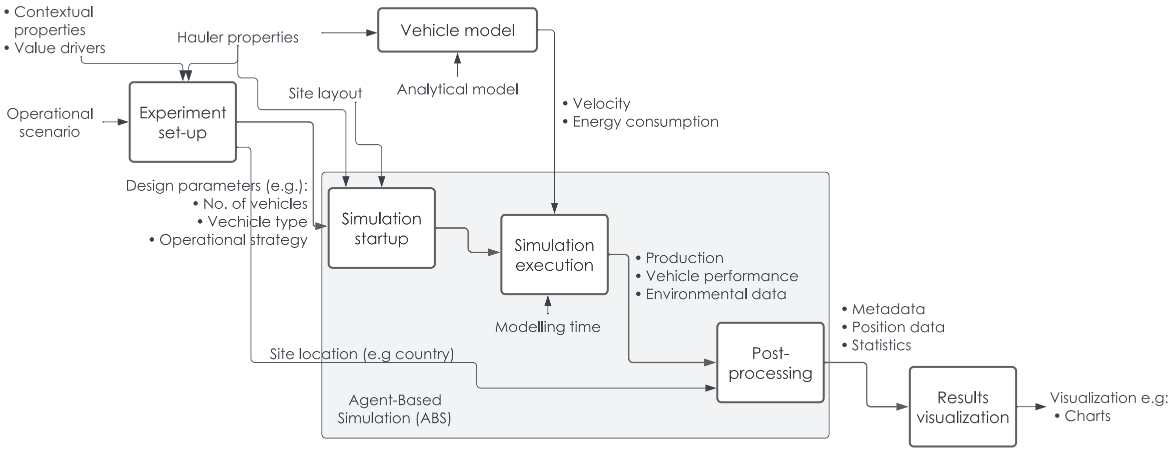


Figure 61 IDEF0 diagram demonstrating how the simulation framework is set up (based on Toller Melén et al. (2024a)).

Before the experiment is initialized, the intended site and its routing must be added to the repository. The first step in the process is the experiment setup, where all design parameters and their options are determined. The next step is then for the simulation model to initialize. The design parameters are imported during this stage, the MATLAB engine is started, and the site is loaded in the context. Further, the model populates the context with all relevant and needed agents (e.g., haulers, wheel loaders, control tower, etc.).

With the experiment configured, the simulation is executed, and the agent acts as pre-programmed based on rules and logic. Vehicle agents will continuously call the analytical models throughout the simulation model time to receive the correct velocity profile and energy consumption according to the set control policies. The control tower agent oversees the operations and assigns all other agents to different activities depending on their current states and operational status. Moreover, digital sensors continuously collect and store the relevant data from all agents (e.g., crusher fill rate, battery state of charge, queuing times, etc.). By the end of the simulations, this data is aggregated and summarized for the next step.

The final step is the post-processing and visualization of the simulation. If a batch run is executed, i.e., exploring multiple scenarios in one experiment, all the meta- and results data is exported and stored in CSV files. These files are then imported into a results model (R language) that transforms, aggregates and derives value metrics for each scenario. These are then visualized using different graphs. The simulation model can also export the position and vehicle states for all haulers in a scenario. These data can then be imported into a VR game engine for visualization.

6.7.5 Integration with vertical work package V1

Concurrently, the project's work package V1 aimed to design a new generation of TAXX vehicles with connected charging infrastructure. Hence, this work has been incorporated into the H4 work package development. This has been mainly done by calibrating the generic vehicle dynamics model using the vehicle models developed by the V1 work team, as described in the V1 results section. In turn, this allows the new vehicle concept to be tested in a site operation setting, thus providing good feedback to the design team on how different design options, e.g., battery size and charging power, impact the operation and value delivery from a SoS and site view.

The collaboration between work package V1 and H4 has enabled the V1 team to enhance their understanding of how system or subsystem design options influence the SoS-level and site value delivery while simultaneously providing the H4 team with calibration data to strengthen the generic vehicle dynamics model and increase its capabilities.

6.7.6 Demonstrative case

Several case studies have been conducted in parallel with the proposed framework’s conceptual development. A demonstrative case study is highlighted to showcase how the proposed hybrid simulation platform can be used in practice. A more detailed case study can be read in (Toller Melén et al., 2024b), one of the papers submitted in this project. To maintain confidentiality, this case study utilizes fictional sites. However, the general profiles and characteristics closely resemble those of existing locations. Figure 62 illustrates a sample route within a site, including its elevation profile. This route is then discretized into segments, representing paths between stations (loading, dumping, and charging). This segmentation allows vehicles to dynamically select a combination of segments based on their current location and target destination. As haulers receive new tasks, they determine the most suitable segment combination. They then query the vehicle dynamics model to calculate the corresponding velocity profile and energy consumption before initiating from the state of rest.

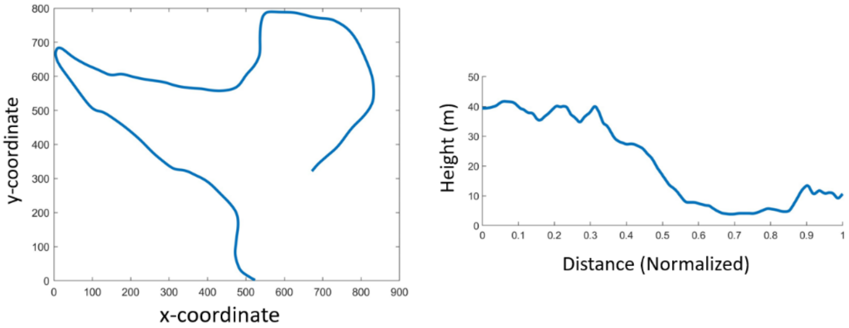


Figure 62 Sample route along with its elevation profile.

Based on the objectives of the simulation, the control tower assigns new tasks to all agents until the predetermined model time is over. As previously stated, the simulation has a set of virtual sensors and data loggers that collect all necessary data on the states and behavior of the operations, e.g., energy consumption, crusher fill rate, queuing times, etc. Following the simulation, a post-processing step extracts and aggregates data from loggers into metrics relevant to the chosen value perspectives. This case study focused on cost, sustainability, and utilization. Refer to (Toller Melén et al., 2024b) for details on the value function and specific metrics used. The aggregated data is then fed into the R software for further processing and visualization. Figure 63 presents the results of this process. The yellow bubbles represent the total normalized value for each operational scenario. The larger the bubble, the higher the value. The blue bubbles depict the average value for a specific fleet configuration across different operational contexts. This provides insight into the average performance of a particular configuration under various conditions. The black triangles highlight infeasible solutions where a combination of fleet configuration and operational context doesn't yield a viable outcome. These solutions are assigned a value metric of zero.

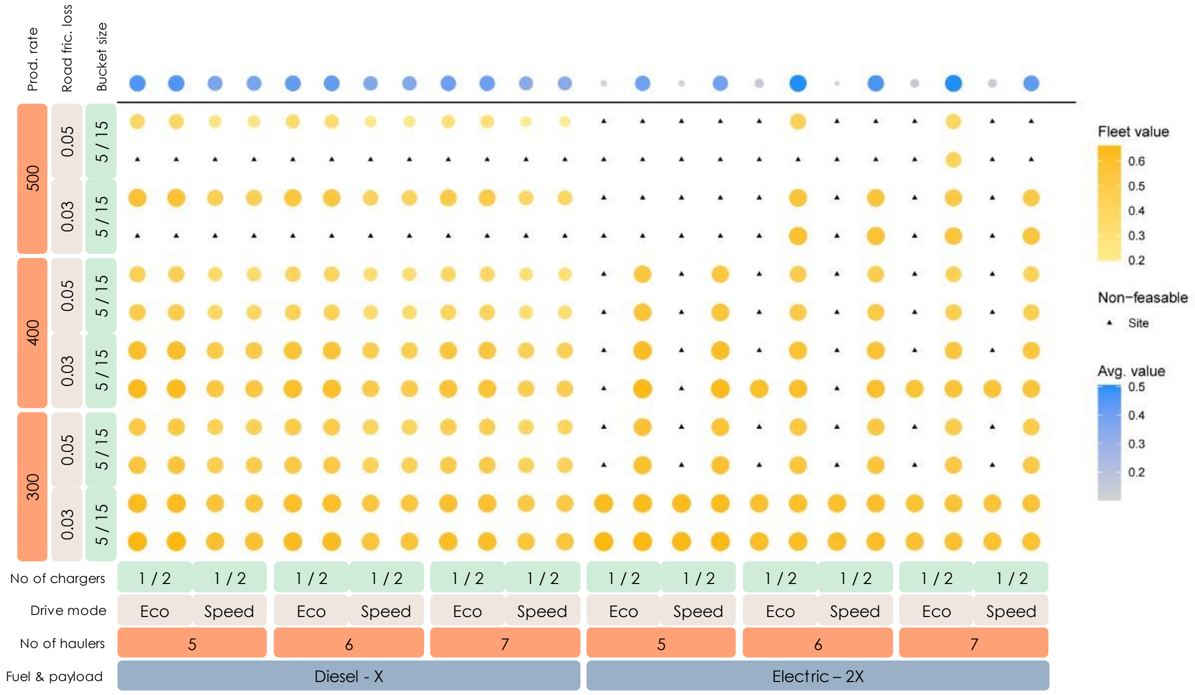


Figure 63 Bubble chart showing the overall and aggregated value of different SoS in various operational conditions.

However, only looking at the overall value might not be sufficient for decision-makers. Hence, the post-processing setup also enables the extraction of top performers for various operational contexts. Figure

64 shows the top six fleet performers extracted and plotted separately. This breakdown complements the average value with the average metrics for all three value perspectives (cost, sustainability, and utilization). This granular view allows the design team to analyze how value creation is achieved for these top performers.

The final part of the case study was to demonstrate the use of VR for enhancing the understanding of different design options and how they would look like at the site. For this purpose, the simulation model was equipped with the possibility of exporting the position and state data that then could be imported by a game engine to provide more immersive visualizations. The visualization was complemented with a dashboard to present the currently viewed simulation scenario as well as its key metrics.

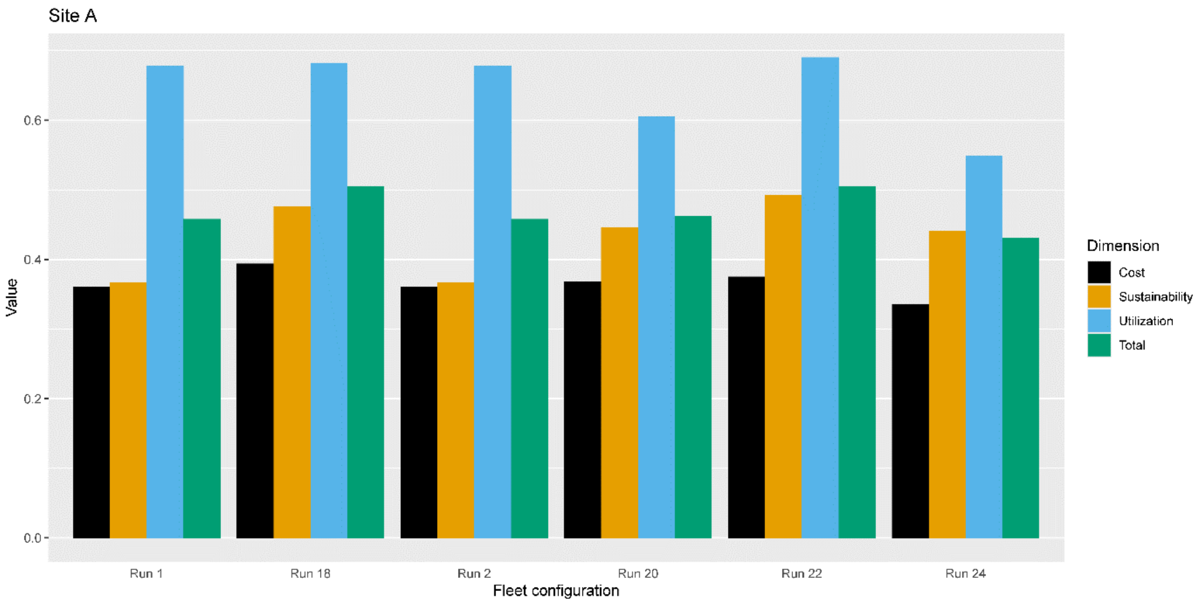


Figure 64 Bar chart comparing the top performers in the dimension of value.

6.7.7 Fulfillment of objectives

Finally, the results and deliverables developed throughout the project have been compared to the previously stated work package objectives. The remainder of this section goes through each objective and how and to what degree it has been fulfilled.

Raise awareness of uncertainties and secondary effects linked to the transition to electromobility and autonomy in terms of aspects linked to product design, economics/business model, and environment.	Completed

The first objective has been met by developing a multi-fidelity simulation framework that can capture interdependencies from an SoS perspective. This allows for uncertainties and secondary effects to be simulated and explore the impact of contextual, system, and operational changes (both structural and temporal) on the overall site performance and value delivery.

Create a set of generic replicable approaches for the simulation (e.g., discrete event, agent-based, system dynamics) of the transition towards electromobility and autonomy that can be implemented in new contexts within a reasonable time.	Completed

The conceptualized framework and architecture provide a generic foundation for modeling and simulating complex SoS using a multi-fidelity and simulation-modeling hybrid framework. The case model has been developed with capabilities for testing trucks, articulated haulers, and autonomous-electric haulers (Taras), both existing and hypothetical machines. The developed models have been designed with respect to flexibility and scalability by testing multiple sites.

Make scenario-based simulations of alternative system configurations available in minutes to assess strengths, weaknesses, threats, and opportunities for value creation and improvement of environmental performance at a site during decision-making meetings.	Completed

The integrated simulation platform developed supports evaluating a wide range of design options and efficiently exploring the design space. The model's strength lies in its ability to perform a comprehensive design sweep within a reasonable timeframe. Notably, re-runs are significantly faster due to the optimization leveraging accumulated data from previous vehicle dynamics simulations (the most computationally expensive step). This not only drastically reduces the need for additional analytical modeling runs but also allows for single-scenario simulations to be completed in minutes and re-runs in seconds.

Realize operational digital twin for real-time flows in an operational environment	Partly

The developed simulation platform does not collect operational data live from sensors but can account for the current operational status at the beginning of the simulation time. A simulation model time is disconnected from real-time and thus does not need a live connection. However, the utilization of game engines and VR has been initially explored, where the model time and real-time are in sync, to obtain a modular DT fully. Even though this has been conceptually described, there is still a need for Proof of Concept with real data integration.

Integrate information flows from the simulated environment to the operational digital environment.	Partly

Similar to the prior objective, this project focused on developing a robust and scalable simulation platform that can eventually be integrated into a modular DT. The approach also involved creating virtual data sensors within the ABS model. These sensors are conceptually designed to mirror real-world SoS boundaries across various operational contexts. The data collected by these sensors can serve as inputs for the operational digital environment and provide the necessary datasets for comparison with their physical counterparts.

6.7.8 Conclusions and next steps

The efforts made in work package H4 have focused on establishing an integrated simulation platform to better understand the autonomy-electric transition in the mining industry. The developed models allow decision-makers to explore and assess different fleet configurations over changing operational contexts to identify the most suitable option from a value perspective (initially incorporating cost, utilization, and sustainability perspectives). The hybrid framework uses virtual sensors to collect data throughout the simulated operations, which are then used to quantify the performance of a given scenario. Finally, the developed framework aims to lower the uncertainties in early design stages by quickly simulating and assessing new sites and operational scenarios and presenting an aggregated value metric for different design options.

To further enhance the capability of the proposed hybrid simulation platform, the next step is to add all different types of machines involved in the mining process, including wheel loaders, excavators, etc. Such a comprehensive selection of vehicles shall enable a more thorough representation of the real mining scenario in the DT. Additionally, validation of the approach in regard to real sites is seen as a vital step in gaining the trust of the decision-makers. However, this will also increase the computational demand, and therefore, it is strategically wise to explore reinforcement learning as an approach for vehicle modeling to lower the computational demands during simulation execution.

Once a comprehensive library of validated machines exists in the DT, different lifecycle activities and strategies can be explored to investigate how different business models, service programs, etc., affect the operations and value creation. Finally, the game engine and VR environment for the DT has only briefly been explored. Enhancing these capabilities can strengthen the capabilities of the modular DT, especially considering the possibilities of adding operator-in-the-loop and bringing the physical and virtual worlds closer together.

7 DISSEMINATION AND PUBLICATIONS

7.1 DISSEMINATION

The project has focused on dissemination of knowledge between the partners, and to employees and visitors at the Volvo Group CampX Innovation Center in Göteborg. Dissemination on a larger scale of the autonomous transport solution within Volvo is managed by the Marketing and Communications team, separate from the project.

In addition to regular digital project meetings, the project team met face-to-face on several occasions, to share knowledge and plan coming activities. The project held a kick-off in CampX in Göteborg, followed by a visit to the Volvo Customer Center in Eskilstuna, where we could see the TA15 machines in action during autonomous operation. We visited Volvo Construction Equipment in Braås, to see the production facilities for the TA15 and talk to the design team for the new TAXX. The short distance between Braås and BTH's facilities in Karlskrona facilitated the work on dynamic vehicle models and site simulation models. The project team held a larger dissemination event in CampX in January 2024, followed by the final demonstration event at Asta Zero near Borås. As several of the partners were in Göteborg, it was easy to meet for smaller workshops and meetings on a more spontaneous one-to-one basis.

Figure 65 Snapshots from the final dissemination event at AstaZero. The project coordinator Cecilia Wendin (Volvo Autonomous Solutions) introduced the day's schedule. Carl Toller Melén presented the findings from the research team at Blekinge Tekniska Högskola. The TA15 took a bow next to the Control room.

Göteborg University and Blekinge Tekniska Högskola have been active in publishing results and attending seminars and conferences.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	There has been much knowledge sharing across industry and academia, increasing knowledge within automotive, connectivity, mining & quarry, teleoperation and requirements management. Two master theses were also performed in connection with the project, both on the topic of charging infrastructure and placement of chargers.
Be passed on to other advanced technological development projects	X	V.A.S. Ericsson Telia and Voysys will continue developing the functions and systems, separately or together. The partnerships and knowledge exchange continues after ASPECT
Be passed on to product development projects	X	The industrial partners will feed the findings, knowledge and solutions into their product development teams.
Introduced on the market	X	V.A.S. is working continuously to industrialize the autonomous transport solution within mining & quarry. The

		results from the ASPECT project will be incorporated into the ongoing development. Market introduction is in progress, with different base vehicles. Ericsson and Telia provide public and private network solutions for the ASPECT project. The network solutions will continue to evolve, and benefit from the learnings from the ASPECT project. Thus, the conclusion is that that it has been very valuable to work together with application developers in a “realistic” scenario to validate the new 5G capabilities.
Used in investigations / regulatory / licensing / political decisions		Long-term this will be relevant, but not directly in connection with this project.

Meetings, workshops & seminars	Date	Location
Kick-off and round-table discussions for the consortium.	Mar 2022	Volvo CampX, Göteborg
Presentation of the value-driven design model by BTH	Dec 2022	Digital meeting
Fazelidehkordi, Y., & Cabrero-Daniel, B. (2023). Digital Twins as a common ground for interdisciplinary sustainability discussions.	2023	10th ACM Celebration of Women in Computing: womENcourage.
Ronanki, K., Cabrero-Daniel, B., Horkoff, J., & Berger, C. (2023). RE-Centric Recommendations for the Development of Trustworthy(Er) Autonomous Systems.	2023	Proceedings of the First International Symposium on Trustworthy Autonomous Systems. Presented at the Edinburgh, United Kingdom. doi:10.1145/3597512.3599697
Demonstration of the TA15 at Customer Center. Initial findings from Ericsson & Telia.	Jan 2023	Volvo Eskilstuna
Presentation of status. Tour of Braås facility and TA15 assembly line.	Aug 2023	BTH Karlskrona; Volvo Braås
Discussed simulation models and V.A.S. product design. Presentation and review of GU requirements elicitation method.	Nov 2023	BTH, Karlskrona
Project seminars: presentation of findings so far Open to project partners and all at Volvo CampX Innovation Center. Demonstration of the modular DT framework’s current capabilities	Jan 2024	Volvo CampX Innovation Center, Göteborg
BTH workshops with V.A.S. experts to collect input on the most critical features to implement	Jan 2024	Volvo CampX, Göteborg
Project meeting & planning	Jan 2024	Volvo CampX, Göteborg
Workshop and presentation of results and master’s thesis- BTH and V.A.S.	April 2024	Volvo CampX, Göteborg
Final demonstration and seminars at AstaZero	May 2024	AstaZero (Borås).

7.2 PUBLICATIONS

Work package H3 (Göteborg University)

O. Ratushniak and B. Cabrero-Daniel, "Designing Digital Twins for Enhanced Reusability," in *Proceedings of the International Conference on Software Engineering (ICSE)*, 2023.

B. Cabrero-Daniel, Y. Fazelidehkordi, and O. Ratushniak, "Trustworthy 'Blackbox' Self-Adaptive Systems," in *Proceedings of the Requirements Engineering: Foundation for Software Quality (REFSQ)*, 2023.

K. Ronanki, "Towards an AI-centric Requirements Engineering Framework for Trustworthy AI," in *Proceedings of the International Conference on Software Engineering (ICSE)*, 2023.

K. Ronanki, B. Cabrero-Daniel, J. Horkoff, and C. Berger, "RE-centric Recommendations for the Development of Trustworthy(er) Autonomous Systems," *arXiv preprint arXiv:2306.01774*, 2023.

K. Ronanki, B. Cabrero-Daniel, J. Horkoff, and C. Berger, "Requirements Engineering using Generative AI: Prompts and Prompting Patterns," 2023.

K. Ronanki, B. Cabrero-Daniel, and C. Berger, "Prompt Smells: An Omen for Undesirable Generative AI Outputs," in *Proceedings of the Conference on Artificial Intelligence (CAIN)*, 2023.

K. Ronanki, B. Cabrero-Daniel, and C. Berger, "ChatGPT as a Tool for User Story Quality Evaluation: Trustworthy Out of the Box?," *arXiv preprint arXiv:2306.12132*, 2023.

Work package H4 (Blekinge Tekniska Högskola)

Toller Melén, C.N.K., Machchhar, R.J., Wendin, C., Bertoni, M., 2024. A framework for context-based System-of-Systems value exploration. Submitted to publication.

Machchhar, R.J., Toller Melén, C.N.K., Bertoni, A., 2024. A tradespace exploration approach for changeability assessment from a system-of-systems perspective: application from the construction machinery industry. Proc. Des. Soc. 4, 2655–2664. https://doi.org/10.1017/pds.2024.268

Toller Melén, C.N.K., Machchhar, R.J., Bertoni, A., 2024. Merging agent-based simulation and vehicle dynamics: a hybrid approach for value exploration in the mining industry. Proc. Des. Soc. 4, 2755–2764. https://doi.org/10.1017/pds.2024.278

Machchhar, R.J., Bertoni, A., Wall, J., Larsson, T., 2024. Incorporating changeability for value-robust product-service systems: an integrative review. Design Science 10, e8. https://doi.org/10.1017/dsj.2024.5

Fredin A, Pogén M. Designing Simulation Model for Open-Pit Mining Charging Infrastructure. 2024. Available from: https://urn.kb.se/resolve?urn=urn:nbn:se:bth-26289

8 CONCLUSIONS AND FUTURE RESEARCH

The ASPECT project has fostered a fruitful collaboration between industrial and academic partners, achieving most of its intended purposes and objectives. We have elevated the TRL levels of various components of Volvo’s autonomous transport solution and reworked it into a platform more suitable for industrialization and scaling. The system is designed to optimize the entire transport process at a specific site, encompassing fleet management, traffic control, charging strategies, and optimal site design.

While the concept of a fully electric autonomous site is beyond Volvo’s mandate to implement, it remains a vision we can present to our customers as electrification progresses. Many mines and quarries have predefined layouts and operational conditions that set boundaries for the type of equipment and transport solutions we can implement. As the global shift to electromobility advances, the relevance of optimized fully electric and autonomous sites will grow.

Teleoperation is a key feature within the autonomous electric site, though its most beneficial applications are still being determined. Seamless transitions between autonomous and teleoperated modes can reduce standstill time, enhancing efficiency. However, the impact on CO_2 emissions is more significant for diesel trucks than for electric machines, which regenerate energy when braking. Thus, teleoperation is currently more of an operational consideration than an energy optimization or GHG emission reduction strategy.

Future studies should focus on implementing teleoperation systems with real vehicles to validate the simulations and frameworks developed in this study. Real-world testing will help understand the practical challenges and effectiveness of seamless handover mechanisms, fleet server robustness, and overall system integration.

By working with different customers, we have developed a method to evaluate a full mining or quarry site from the perspective of autonomous and electric transport solutions, creating optimized site designs and processes. Several components of the transport system have been modularized, allowing for adaptation to each customer site.

Predicting the behavior of the autonomous electric solution in detail once operational is challenging due to the lack of historical data. Both Volvo and its customers need to understand the total cost of ownership and operation before investing in an electric and autonomous transport service. Digital twins can simulate different scenarios, speeding up software and hardware development and allowing for site simulation before construction. BTH and Volvo have laid the groundwork for digital twins, demonstrating their use in representing different sites and conditions and supporting optimal fleet configuration evaluations

A key lesson from partner discussions is the varied definitions and purposes of “digital twin.” The application of digital twins ranges from development and verification to early site assessment and planning, culminating in connected digital twins for predictive maintenance and operational fine-tuning. Creating a digital twin of the real world is complex, but by segmenting it for different purposes, multiple digital twins can provide diverse data and decision inputs. This has been described in the method defined by Göteborg University.

In the current V.A.S. ATS version, Volvo controls the full transport solution, with confined areas containing only autonomous and low-speed manual machines. Future development will enable higher-speed interactions between autonomous and manual vehicles. To reach new markets, we designed a new, larger electric hauler for integration into the autonomous transport solution. Further work and planning within the Volvo Group are needed.

True energy optimization of a site, integrating state-of-charge information and active planning based on energy requirements, prices, and available power, is a long-term vision. Developing an autonomous transport solution for various confined areas, managing complex risk and liability issues, and operating in harsh physical environments is challenging. The first step is to deploy the solution at several sites, followed by industrialization and scaling. As more data and lessons are gathered, further tuning and optimization will become relevant. Applying machine learning and AI to path planning, combined with vehicle-to-vehicle communication, is of interest for creating a truly autonomous and energy-optimized system and site.

Mobile networks meeting specific communication requirements for different components in a confined area are essential for deploying the autonomous transport solution. The 5G SA cellular network can provide the needed communication for the digitalized site. By taking a holistic view of all services related to the site the communication services can be provided in the most efficient manner. Future studies should focus on enhanced functionality in the 5G network to achieve effective, sustainable and cost efficient communication and services. We have demonstrated that the network can be configured to meet various needs, though more real-world data is needed. The total cost of on-site infrastructure will be a key factor for future customers and may influence which customers and sites are suitable for autonomous and electric transport solutions.

A key takeaway from the project has been the valuable discussions and knowledge sharing between partners. For Swedish industrial companies, investment in new innovations often occurs regardless of external funding. However, participating in these projects enhances information exchange between industry and academia, raising our collective innovation capacity. Balancing different timelines and priorities between business and academic settings is challenging, but we found a good balance within the ASPECT project.

The partners thank each other, FFI, and Vinnova for the successful project completion. Although no immediate plans for common next steps have been defined, we are confident that each party will carry the learnings from ASPECT into their future work. We also thank the master’s thesis students who collaborated with the project and wish them success in their future endeavors.

9 REFERENCES

9.1 REFERENCES FOR WORK PACKAGE H2

Ericsson, "Time-Critical Communication Leading the Next Wave of 5G Innovation," Available at: https://www.ericsson.com/4a9e9f/assets/local/internet-of-things/docs/19102021-time-critical-communication-brochure.pdf (Accessed: 2024-09-13).

ITU, "IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Available at: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf (Accessed: 2024-09-13).

Ericsson, "Critical IoT for Time-Critical Communications," Available at: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/critical-iot-connectivity (Accessed: 2024-09-13).

3GPP, "5G Service Requirements for Cyber-Physical Control Applications in Vertical Domains," Available at: https://www.3gpp.org/ftp/Specs/archive/22_series/22.104/22104-h70.zip (Accessed: 2024-09-13).

5G ACIA, "5G ACIA White Paper – 5G Non-Public Networks for Industrial Scenarios," Available at: https://5g-acia.org/wp-content/uploads/5G-ACIA_5G_Non-Public_Networks_for_Industrial_Scenarios_09-2021.pdf (Accessed: 2024-09-13).

3GPP, "System Architecture for the 5G System (5GS)," Available at: https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/23501-h70.zip (Accessed: 2024-09-13).

Vinnova, "Cybersecurity for Control Communication Protection (C3P)," Available at: https://www.vinnova.se/p/cybersecurity-for-control-communication-protection-cccp/ (Accessed: 2024-09-13).

9.2 REFERENCES FOR WORK PACKAGE H4

Avison, D.E., Lau, F., Myers, M.D., Nielsen, P.A., 1999. Action research. Commun. ACM 42, 9497. https://doi.org/10.1145/291469.291479

Borshchev, A., Filippov, A., 2004. From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. Presented at the 22nd international conference of the system dynamics society, Oxford, England, pp. 25–29.

Bradbury, H., 2015. The SAGE Handbook of Action Research. SAGE Publications Ltd, 1 Oliver's Yard, 55 City Road London EC1Y 1SP. https://doi.org/10.4135/9781473921290

Caterpillar, 2021. Cat® MineStar™ Automation Solutions. URL https://www.cat.com/en_US/by-industry/mining/minestar-solutions/automation.html (accessed 11.3.23).

Frank, M., Ruvald, R., Johansson, C., Larsson, T., Larsson, A., 2019. Towards autonomous construction equipment - supporting on-site collaboration between automatons and humans. Int. J. Prod. Dev. 23, 292. https://doi.org/10.1504/IJPD.2019.105496

Geng, R., Li, M., Hu, Z., Han, Z., Zheng, R., 2022. Digital Twin in smart manufacturing: remote control and virtual machining using VR and AR technologies. Struct. Multidiscip. Optim. 65, 321. https://doi.org/10.1007/s00158-022-03426-3

Guzzella, L., Sciarretta, A., 2007. Vehicle Propulsion Systems: Introduction to Modeling and Optimization. Springer Science & Business Media.

Hazrathosseini, A., Moradi Afrapoli, A., 2023. The advent of digital twins in surface mining: Its time has finally arrived. Resour. Policy 80, 103155. https://doi.org/10.1016/j.resourpol.2022.103155

Hester, P.T., Tolk, A., 2010. Applying methods of the M&S spectrum for complex systems engineering, in: Proceedings of the 2010 Spring Simulation Multiconference. Presented at the SpringSim ’10: 2010 Spring Simulation Conference, Society for Computer Simulation International, Orlando Florida, pp. 1–8. https://doi.org/10.1145/1878537.1878615

Javaid, M., Haleem, A., Suman, R., 2023. Digital Twin applications toward Industry 4.0: A Review. Cogn. Robot. 3, 71–92. https://doi.org/10.1016/j.cogr.2023.04.003

Komatsu, 2023. Komatsu Autonomous Haulage System. URL https://www.komatsu.com.au/innovation/autonomous-haulage-system (accessed 11.3.23).

Law, A.M., 2015. Simulation modeling and analysis, Fifth edition. ed, McGraw-Hill series in industrial engineering and management science. McGraw-Hill Education, New York, NY.

Lima, L., Trindade, E., Alencar, L., Alencar, M., Silva, L., 2021. Sustainability in the construction industry: A systematic review of the literature. J. Clean. Prod. 289, 125730. https://doi.org/10.1016/j.jclepro.2020.125730

Machchhar, R.J., Toller Melén, C.N.K., Bertoni, A., 2024. A tradespace exploration approach for changeability assessment from a system-of-systems perspective: application from the construction machinery industry. Proc. Des. Soc. 4, 2655–2664. https://doi.org/10.1017/pds.2024.268

Panarotto, M., Isaksson, O., Vial, V., 2023. Cost-efficient digital twins for design space exploration: A modular platform approach. Comput. Ind. 145, 103813. https://doi.org/10.1016/j.compind.2022.103813

Shanthikumar, J.G., Sargent, R.G., 1983. A Unifying View of Hybrid Simulation/Analytic Models and Modeling. Oper. Res. 31, 1030–1052. https://doi.org/10.1287/opre.31.6.1030

Siebers, P.O., Macal, C.M., Garnett, J., Buxton, D., Pidd, M., 2010. Discrete-event simulation is dead, long live agent-based simulation! J. Simul. 4, 204–210. https://doi.org/10.1057/jos.2010.14

Toller Melén, C.N.K., Machchhar, R.J., Bertoni, A., 2024a. Merging agent-based simulation and vehicle dynamics: a hybrid approach for value exploration in the mining industry. Proc. Des. Soc. 4, 2755–2764. https://doi.org/10.1017/pds.2024.278

Toller Melén, C.N.K., Machchhar, R.J., Wendin, C., Bertoni, M., 2024b. A framework for context-based System-of-Systems value exploration. Submitt. Publ.

Volvo Autonomous Solutions, 2023. Autonomous haulage system for quarries, mining & industrial material handling. URL https://www.volvoautonomoussolutions.com/en-en/our-solutions/autonomous-transport-solution-by-volvo/quarries-mining-and-industrial-material-handling.html (accessed 11.3.23).

Volvo Construction Equipment, 2021. Electric and autonomous heavy equipment: the future of construction and mining. URL https://volvoceblog.com/electric-and-autonomous-heavy-equipment-the-future-of-construction-and-mining/ (accessed 11.3.23).

Zhang, J., Cheng, J.C.P., Chen, W., Chen, K., 2022. Digital Twins for Construction Sites: Concepts, LoD Definition, and Applications. J. Manag. Eng. 38, 04021094. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000948

10 PARTICIPATING PARTIES AND CONTACT PERSONS

VOLVO	Cecilia Wendin (V.A.S.) Marcus Andersson (Volvo CE)
Telia Company	Tomas Bergqvist
ERICSSON	Daniel McGillivray
UNIVERSITY OF GOTHENBURG	Professor Christian Berger
BLEKINGE TEKNISKA HÖGSKOLA · BTH ·	Professor Tobias Larsson
voysys	Torkel Danielsson