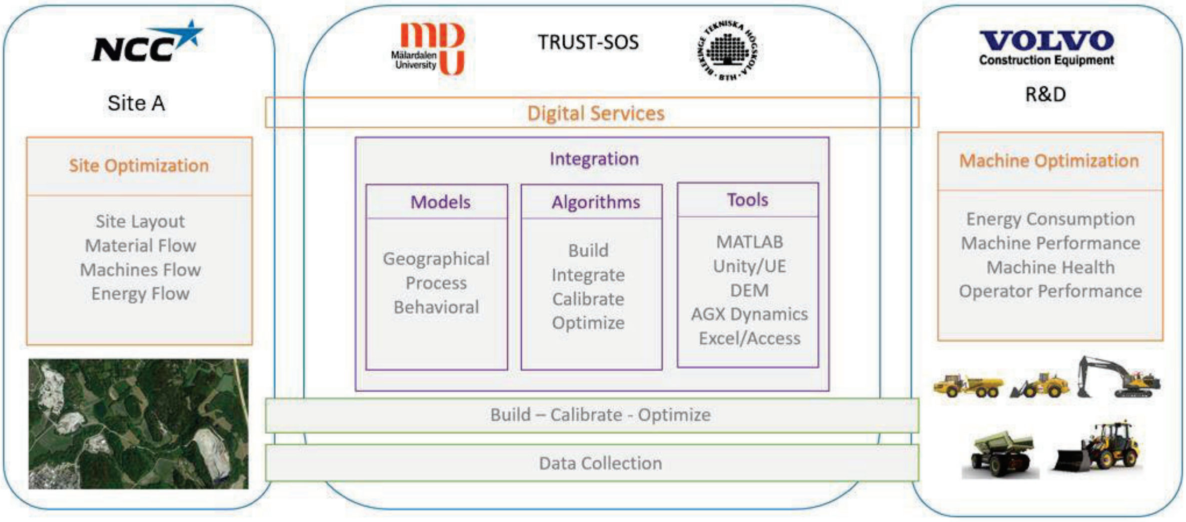
TRUST-SOS

Trusted Site Optimisation Solutions

(Nov 2021-Dec 2024)



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https://www.vinnova.se/p/trust-sos/
https://www.ipr.mdu.se/projects/587-TRUST_SOS___TRUSTed_Site_Optimisation_Solutions
https://www.bth.se/forskning/forskningsprojekt/trust-sos-trusted-site-optimisation-solutions/

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1 Summary in Swedish

Projektet TRUST-SOS syftade till att optimera transporter i bergtäkter och liknande miljöer genom att utveckla ett digitaliserat, modellbaserat beslutsstödssystem. Traditionell verksamhet förlitar sig i hög grad på erfarenhetsbaserat beslutsfattande, som ofta involverar ett fåtal skickliga personer för att fatta kritiska operativa beslut. Detta system skapar ineffektivitet och gör det utmanande att hantera komplexiteten hos dynamiska, storskaliga arbetsplatser. TRUST-SOS-projektet försökte ta itu med dessa utmaningar genom att övergå från erfarenhetsbaserat beslutsfattande till datadrivna, modellbaserade tillvägagångssätt och skapa ett mer tillförlitligt och effektivt system för hantering av bergtäkter.

Projektet integrerade maskin- och site-simulering och optimeringstekniker för att utveckla digitaliserade tjänster för transportapplikationer. Genom att utnyttja realtidsdata och avancerad analys skapade TRUST-SOS prediktiva verktyg och simuleringar som möjliggjör optimering av drift, resursutnyttjande och miljöpåverkan. Systemet tar hänsyn till olika faktorer, inklusive operatörens skicklighet, enheters prestanda och terrängförhållanden, för att möjliggöra simulering och beslutsfattande som förbättrar produktiviteten, minskar bränsleförbrukningen och minimerar miljöpåverkan.

En viktig nyhet i TRUST-SOS-projektet var skapandet av modulära fordons- och mobilitetsmodeller. Dessa modeller stödjer beslutsfattande för hela anläggningen, inklusive maskinprestanda, operatörens skicklighet och materialinteraktion. De möjliggör prestandaövervakning av fordon och maskiner, optimering av driftsparametrar och underlättar planering och konfigurering av nya byggarbetsplatser. Dessa modeller möjliggör också optimering av byggarbetsplatsens prestanda, med hänsyn till olika driftsförhållanden och maskintyper för att maximera effektiviteten och minimera kostnader och miljöpåverkan.

Förutom den tekniska utvecklingen bidrog projektet till utvecklingen av affärsmodeller och digitaliserade tjänster som stämmer överens med kundernas behov och verksamhetsmål. Dessa tjänster har utformats för att erbjuda mervärden såsom prediktivt underhåll, prestandaövervakning och driftsoptimering. Genom att gå från erfarenhetsbaserade processer till modellbaserade, datadrivna tjänster optimerade TRUST-SOS inte bara verksamheten utan introducerade också nya intäktsströmmar och affärsmöjligheter för intressenter inom terrängtransportbranschen.

Under hela projektet låg fokus på hållbarhet och energieffektivitet, i linje med målen för delprogrammet Vinnova FFI för att främja utveckling och marknadsintroduktion av fossilfria arbetsmaskiner. TRUST-SOS-projektets digitaliserade tjänster bidrar till att minska klimatutsläppen genom att optimera maskinanvändningen, möjliggöra övergången till och stödja införandet av elektriska maskiner. Dessutom, genom att förbättra systemets effektivitet och stödja automatisering, bidrog projektet till att minska beroendet av fossila bränslen, vilket banar väg för mer hållbar och effektiv bergtäktsdrift.

Projektet fokuserade på digital tjänstefiering, utveckling av affärsmodeller som skulle kunna omvandla traditionell verksamhet till tjänsteorienterade lösningar. Detta tillvägagångssätt möjliggör kontinuerligt kundengagemang genom digitala tjänster, såsom prestandaoptimering och prediktivt underhåll. Genom att utforska datadrivna tjänsteerbjudanden hjälpte TRUST-SOS till att skapa ett flexibelt, skalbart tillvägagångssätt för att hantera off-road-transporter, vilket säkerställer att intressenter kan anpassa sig till förändrade marknadsbehov.

Resultaten av TRUST-SOS-projektet har potential att avsevärt påverka off-road-transportindustrin genom att optimera driften av siten och maskinprestanda samtidigt som miljöpåverkan minskar. Projektet visade hur digitalisering, simulering och avancerad analys kan tillämpas på traditionella industrier för att skapa mer hållbara, effektiva och kostnadseffektiva verksamheter. Med sitt fokus på hållbarhet, automatisering och digitala tjänster bidrog TRUST-SOS-projektet till det bredare målet att utveckla fossilfria arbetsmaskiner, vilket positionerar Sverige som ledande i omställningen till mer hållbara industriella metoder.

Fortsatt forskning och utveckling efter projektet skulle kunna utforska utvecklingen av mer avancerade maskininlärningsmodeller och ökad användning av artificiell intelligens för att förbättra beslutsstödsystemets prediktiva förmåga. Dessutom kan kommande projekt driva på ytterligare

innovation inom elektriska maskiner för off-road-tillämpningar, vilket gör det möjligt för industrin att snabbare övergå till fossilfri verksamhet.

2 Executive Summary in English

The **TRUST-SOS project** aimed to optimize off-road transport operations in quarries and similar environments by developing a digitalized, model-based decision support system. Traditional off-road operations relied heavily on experience-based decision-making, often involving a few skilled individuals to make critical operational decisions. This system creates inefficiencies and makes it challenging to manage the complexities of dynamic, large-scale work sites. The TRUST-SOS project sought to address these challenges by transitioning from experience-based decision-making to data-driven, model-based approaches, creating a more reliable and efficient system for quarry site management.

The project integrated site modelling, machine and site simulation, and optimisation techniques to develop digitalized services for off-road transport applications. By leveraging data and advanced analytics, TRUST-SOS created predictive tools and simulations that allows for the optimisation of site operations, resource utilization, and environmental impact. The system accounts for various site factors, including operator skill, asset performance, and terrain conditions, to enable simulation and decision-making that improves productivity, reduces fuel consumption, and minimizes environmental impact.

A key innovation of the TRUST-SOS project was the creation of **modular vehicle and mobility models**. These models support decision-making for the entire site, including machine performance, operator skill, and material interaction. They enable performance monitoring of vehicles and machines, optimisation of the operating parameters, and facilitates planning and configuration of new construction sites. These models also allowed for the optimisation of construction site performance, considering various operating conditions and machine types to maximize efficiency and minimize costs and environmental impact.

In addition to the technical development, the project contributed to the development of business models and digitalized services that align with customer needs and operational goals. These services were designed to offer value-added functionalities, such as predictive maintenance, performance tracking, and operational optimisation. By transitioning from experience-based processes to model-based, data-driven services, TRUST-SOS not only optimized operations but also introduced new revenue streams and business opportunities for stakeholders in the off-road transport industry.

Throughout the project, there was a strong focus on **sustainability** and **energy efficiency**, aligning with the objectives of the Vinnova FFI sub-program to promote the development and market introduction of fossil-free work machines. The TRUST-SOS project's digitalized services contribute to reducing climate emissions by optimizing machine usage, enabling the transition towards electrification, and supporting the adoption of electric machines. Additionally, by improving system efficiency and supporting automation, the project helped reduce the reliance on fossil fuels, paving the way for more sustainable and efficient quarry operations.

The project focused on **digital servitisation**, developing business models that could transform traditional operations into service-oriented solutions. This approach allows for continuous customer engagement through digital services, such as performance optimisation and predictive maintenance. By exploring data-driven service offerings, TRUST-SOS helped create a flexible, scalable approach to managing off-road transport operations, ensuring that stakeholders can adapt to evolving market needs.

The results of the TRUST-SOS project have the potential to significantly impact the off-road transport industries by optimizing site management and machine performance while reducing environmental impact. The project demonstrated how digitalization, simulation, and advanced analytics could be applied to traditional industries to create more sustainable, efficient, and cost-effective operations. With its focus on sustainability, automation, and digital servitisation, the TRUST-SOS project contributed to the broader goal of developing fossil-free work machines, positioning Sweden as a leader in the transition to more sustainable industrial practices.

Continued research and development following the project could explore the development of more advanced **machine learning models** and greater use of **artificial intelligence** to enhance the decision support system's predictive capabilities. In addition, projects could drive further innovation in **electric machinery** for off-road applications, enabling the industry to transition more rapidly to fossil-free operations.

3 Background

Today, off-road sites and fleet operations involve a high degree of experience-based decision making to create the optimal usage of equipment and resources at the site and to reduce inefficiencies. Several stakeholders in the value chain rely today on a few skilled people for decision-making of these complex and dynamic sites and experienced-based understanding of the impact on different trade-offs. Hence, the TRUST-SOS project was proposed to overcome the existing system inefficiencies and build a more reliable and trusted decision support system to reduce inefficiencies and manage complexity in the value chain in off-road applications.

TRUST–SOS combined machine, fleet and site modelling, simulation and optimisation to create digitalized services for the off-road transport application. By developing data-driven models for simulation and optimisation of customer site operations, combined with advanced data analytics, we have moved from the current experience-based process to a model-based process that will enable us to deliver customer value in terms of services and trusted decision support.

4 Purpose, Research Questions and Method

The objective of the TRUST–SOS project is to develop digitalized services to increase the level of trusted decision making and to optimize overall site systems in off-road transport applications.

4.1 Research questions

- How can machine models be developed to accurately simulate the behaviour of different types of machines (e.g., loaders, dump trucks) under various site conditions?
- How can interaction models be developed to capture the relationship between machines, operators, materials, and environmental factors (e.g., weather, gravel pile, ground conditions) to improve real-time decision-making and optimize site performance?
- How can site models be developed to accurately represent different working spots (e.g., loading, dumping, charging) and their workflows, allowing for optimisation of task sequencing and resource allocation across the entire quarry site?
- What are the best approaches for integrating site models into a unified simulation to optimize overall site operations?
- How can simulation models be effectively used to predict and optimize the performance of off-road transport systems under varying site conditions?
- What optimisation algorithms are most effective for balancing multiple factors such as machine performance, fuel consumption, and environmental impact in real-time quarry operations?
- How can digital servitisation models be developed to create sustainable business models that deliver continuous value to customers in the off-road transport sector?

4.2 Methods

Design Science Research (DSR) in Information Systems (IS) is a methodological approach that focuses on the creation and evaluation of artifacts—such as models, methods, or tools—that solve specific organizational or technological problems. This approach is particularly well-suited for answering the research questions posed by the TRUST-SOS project because it combines the design of innovative solutions with a rigorous evaluation process, ensuring that the developed systems are both practical and theoretically grounded. Moreover, by emphasising stakeholder engagement and real-world testing, DSR ensures that the solutions are both practical and innovative.

However, design decisions and the design process which TRUST-SOS addresses is in nature a creative, social, and cyclic process. Therefore, was DSR complemented with Action Research (AR). AR can be described as a practical research approach that aims to combine theory and practice in a collaborative research-practitioner environment. Further, AR has a natural resemblance with the design process due to its cyclic approach and ambition to render both knowledge and deliverables concurrently. It couples action and reflection, theory and practice, with a focus on creating practical solutions to pressing concerns.

In the case of the TRUST-SOS project, collaboration between stakeholders from industry and academia was essential to identify business needs and gather the necessary knowledge to inform the research. Industry stakeholders, including equipment manufacturers and off-road site managers, contributed through interviews, workshops, and debriefs to provide insights into operational challenges, decision-making processes, and site-specific requirements. These interactions help ensure that the developed artifacts address real-world needs and are aligned with industry goals. Simultaneously, academic stakeholders conducted literature surveys to identify relevant theories and methodologies that can be used to model complex site operations, machine performance, and workflows. By combining practical insights from industry with theoretical frameworks from academia, DSR and AR allowed for the formulation of a well-defined problem and the development of solutions that are grounded in both empirical data and established knowledge while still rendering practical solutions.

5 Goals

The TRUST-SOS project has the following goals:

- Goal 1. Map and collect data from suitable customers.
- Goal 2. Model a complete quarry site including hauling, loading, excavating and scheduling models.
- Goal 3. Create a modular simulation environment that represents typical operations of off-road applications and includes KPIs such as productivity, energy consumption, emissions, and value creation.
- Goal 4. Develop a site optimisation model for planning new sites and impact assessment of existing sites.
- Goal 5. Identify and define digitalized services and suitable business models based on the developed models.
- Goal 6. Validate the proposed digital platform on a real demonstration.

Table 1 comments on the project goals as stated in the application with potential changes.

Table 1: Project goals as stated in the application with potential changes

The goal for the project as written in the application	The goal has changed	Comment
Goal 1		Two sites were visited to collect data as part of Goal 1. At the site level, comprehensive data on workflows, material flows, and operational conditions were successfully gathered. However, collecting machine-level data proved more challenging due to limitations in accessing detailed operational logs, sensor data, and real-time performance metrics from the equipment.

Goal 2		Models for hauling and scheduling were successfully developed, providing a foundation for optimizing resource allocation and operational efficiency in quarry site operations. Progress in developing models for loading and excavating has been substantial, with efforts focused on accurately simulating material interaction under varying site conditions. Additionally, unplanned but valuable models were developed, such as a dynamic multi-layer site map, which captures detailed spatial and operational data for real-time site management, and a torque prediction model for wheel loader engines, enabling more efficient machine operation through enhanced engine performance insights.
Goal 3		Two simulation environments were proposed and developed to achieve Goal 3, focusing on representing typical operations in off-road applications while incorporating key performance indicators (KPIs) such as productivity, energy consumption, emissions, and value creation. The first environment is based on Discrete-Event Simulation (DES), which models operations as a sequence of discrete events occurring over time. This environment is well-suited for analysing site-level workflows, task scheduling, and resource utilization, providing insights into the efficiency of operations and enabling the optimisation of processes such as hauling, loading, and material transport. The second environment is based on Agent-Based Simulation (ABS), which focuses on simulating the behaviours and interactions of individual entities, such as machines, operators, and materials, within the quarry. This approach captures the dynamic and decentralized nature of off-road applications, allowing for detailed analysis of how autonomous machines and human operators respond to changing site conditions, machine performance, and environmental factors. The development of the architecture for these simulation environments required more time than initially planned due to the complexity of integrating diverse modelling approaches and the DES and ABS frameworks. However, the efforts have created a modular and scalable architecture that can more rapidly be adjusted to fit potential future needs.
Goal 4		A comprehensive site optimisation framework was developed to support the planning of new sites and the impact assessment of existing operations. The framework enables the creation and integration of critical parameters such as site layout, machine configurations, material flows, and environmental conditions to evaluate and optimize site performance. It incorporates key metrics like productivity, cost efficiency, energy consumption, and environmental impact to enable informed decision-making during site design and operational adjustments. Additional effort is required to ensure that the proposed framework is adaptable and effectively integrable with the operational data of off-road applications. Site, fleet and machine optimisation are all manageable within the framework. For the site optimisation, the project focused

		on fleet and infrastructure optimisation due to the complexity of the scope. Full site design and optimization will be part of the continued work in an already launched follow-up project.
Goal 5		As part of Goal 5, efforts were made to identify and define digitalized services and suitable business models based on the developed models. These services were envisioned to leverage real-time decision support, predictive analytics, and optimisation tools to improve operational efficiency, reduce costs, and enhance sustainability in off-road applications. Business models were designed to focus on delivering value through service-oriented approaches, enabling customers to optimize their operations and adopt more sustainable practices.
Goal 6	x	As part of Goal 6, the proposed digital platform was planned to be validated through a real-world demonstration to assess its performance and practical applicability. The demonstration aimed to test the platform's capabilities in optimizing site operations, monitoring machine performance, and providing actionable decision support. This process allowed for evaluating the platform's effectiveness in addressing key performance indicators such as productivity, energy efficiency, and emissions reduction in a real operational setting. However, the validation phase encountered challenges including ensuring seamless integration of the platform with existing systems, addressing data compatibility issues, and fine-tuning the platform to reflect real-world complexities accurately. Despite these challenges, we were able to validate the platform offline using the collected data and ensure the platform's reliability, scalability, and readiness for broader adoption in off-road applications.

5.1 Results by work package

This section presents the main results of all work packages.

The data used for the machine and system models is based on publicly available data to create generic machine models. These models can then be calibrated using proprietary OEM models or collected operational data. Noteworthy, the machine models are calibrated individually in isolation which means that the site simulation can still deviate from real world if the operation and control policy changes. This allows to greater flexibility and scalability.

5.1.1 WP1 Administration

The collaborative approach, characterized by regular and effective communication between researchers from MDU and BTH, as well as staff from Volvo CE and NCC, played a pivotal role in the project's seamless management and execution. This collaboration ensured adherence to the original plan without major deviations.

During the project, one teams workshop, eight face-to-face workshops and three site visits were conducted to understand the customer operations, to set a clear view on the project goals and to build an understanding of the necessary modules to develop in this project. The project also had weekly debriefs to monitor progress and address potential issues. Additionally, every work package held their own meetings and workshops to progress according to the overall project plan.

Due to the complexity of the task, leading to a longer learning path in the beginning of the project, and the initial struggles to secure PhD candidates for the project, a large portion of the development work has been conducted during the latter half of the project. This is reflected in the financial and status reports sent in during the project.

5.1.2 WP2 Customer Site Mapping

Two sites were selected by Volvo CE and NCC for data collection and demonstration in this project: Site A and Site B. The decision to use two sites was taken to encourage modularity in the developed tool and to avoid developing a site-specific solution. It was also a way to demonstrate the flexibility of the developed platform. To exemplify, one site has long transports with trucks, material loading with excavator and uses silos for material storage. The other one uses stockpiles for material storage, a wheel loader for material loading and has shorter transportation distance. The sites were also chosen with an ambition to find personnel with a willingness to test and adopt new digital solutions to best utilize end-user process knowledge and to create buy-in for testing a new approach.

Project members conducted site visits to both locations to collect relevant data (Operating Machines, Scheduling, Workflows, KPIs, etc.) and later in the project to demonstrate our developed models and simulation environments for the end-user.

One site was used for developing the site/fleet /machine optimisation tool and the other site served as a site for verification and validation of the models and simulation. NCC shared data related to the current processes and the research team did measurements, collected data and built the virtual models and representations of the two sites.

Primary work tasks (e.g. loading, hauling etc.) are rather easy to map. However, secondary works tasks, such as e.g. road maintenance, are much more difficult due to the frequency of performing these kinds of tasks. These tasks are also harder to include in the simulation models as they tend to involve more complex behaviour. This makes the modelling of the site and the asset utilization much more difficult than the initial hypothesis in the project. This was addressed in the project by making conscious decisions in simplifying the reality, however the effect on the virtual decision support tool developed is that the human in the control loop, as an evaluator, becomes key at this stage, until a complete virtual model can be implemented. Moreover, as the main work task stands for most of the quarry's operation and value creation, the simulation model still provides essential insights to the site manager. It is, however, important to inform the end user of simplifications and limitations of the virtual support tool. This further emphasizes the ambition to create an "enhancement tool", rather than a "replacement tool" of the human. The digitalization will thus put more focus on using skilled human labour to enhance the operation and give the site manager the data and knowledge to take more educated fact-based decisions rather than, potentially costly, "trial and error" real tests.

An important outcome from the site visits and mapping was that the environmental and production boundary conditions is changing a lot throughout the year. Hence the important insight that "epoch- and era" (short and long-term uncertainties) needs to be implemented. Also, the solution space is large, due to the multi-dimensional nature of the operation, meaning that a computational strategy, that can cater for that, needs to be considered, as well as measures for computational efficiency.

5.1.3 WP3 Site Modelling

A quarry consists of multiple machines, systems, and aspects that influence the operations and their performance. To simulate operations and assess the performance of the current state and potential future states, an array of models needed to be developed. Following are all the models that together form the platform of the simulation tools and digital services for informed decision-making:

- **Load receiver models:** The main transportation of material is done through load receivers, and, therefore, a significant effort has been spent on modelling these. The following haulers have been modelled: Diesel trucks (FMX), diesel articulated haulers (AG), and electric autonomous haulers (TA). More information about their modelling is available in the WP4 results.

- **Load carrier model:** Wheel loaders have been modelled as the load carriers in the simulation. Here, both the material interaction, attachment tipping, and movement between the pile and load receiver are included in the model to render a reasonable estimate of the operations and energy consumption. More information about the wheel loader model is available in WP4 results.
- **Crusher model:** The infrastructure models include the crushers and charging/fuelling station. The crusher was set up to be either stationary or mobile with a static crushing speed equivalent to the set production rate of a given scenario.
- **Charging/refuelling model: The charging/refuelling** model consists of either a charging pole with a given power output or a fuel pump with a constant flow rate. The charging pole used a simple charging function that accounted for the replenishment of the machine's capacity limit as well as efficiency losses.
- **Station model:** The stations dictate what a specific location is hosting regarding work tasks, e.g., loading, dumping, or charging. The station model is a fictive representation of a geographical location and may, therefore, not represent a physical entity. The station model is also used to manage any queueing that might occur.
- **Path model:** Paths and segments are essential for running and simulating the operations. The paths are a collection of segments represented as a list of position points. All movements are made using predefined paths, except for the local movement of the wheel loader in hauler loading. The paths are either defined directly in cartesian coordinates or converted from latitude and longitude coordinates
- **Environment model:** There are multiple contextual and environmental parameters that influence the operation of a quarry. The environment model aims to capture the most relevant parameters, which for this project have been identified as: ambient temperature, road frictional coefficient, and road frictional loss. Information regarding the loading pile is also stored here, e.g., pile density and slope.
- **Control tower/Operations model:** The operation in the simulation is managed by a control tower. The tower will actively communicate with the different systems to obtain status, assign work tasks, and evaluate optimal production. It is the control tower that manages the scheduling and dictates which machine should do, what and where. A dynamic multi-layer map was developed to support advanced autonomous solutions, integrating terrain geometry, real-time road friction updates, material distribution, and optimized traffic routing. This map dynamically updates using sensor data and simulation feedback, enabling real-time adaptability to changing conditions. Integrated with digital twin platforms, the model enhances decision-making for routing, loading, and dumping tasks while supporting scenario testing for extreme conditions, ultimately improving efficiency and sustainability in quarry operations.
- **KPIs models:** Key Performance Indicators (KPIs) for off-road site operations include Fuel Consumption (FC), Material Handling Efficiency (MHE), Cycle Time Optimisation (CTO), Operational Downtime (OD), and Environmental Impact (EI), such as CO_2 emissions. Efficient torque prediction in wheel loader engines plays a critical role in estimating and optimizing Fuel Consumption, as torque directly influences engine load, fuel usage, and operational efficiency. By predicting torque accurately in real-time, it becomes possible to adjust engine performance dynamically, minimizing excessive fuel usage during high-load tasks and improving fuel-to-output efficiency. This predictive capability also contributes to optimizing Cycle Time by ensuring smooth transitions and peak performance during loading and hauling, reducing idle time and energy waste. Additionally, accurate torque predictions support Material Handling Efficiency by maintaining optimal engine operation, reducing wear and tear, and ensuring consistent productivity, all of which align with sustainability and cost-reduction goals in quarry site management.

At the site level, a value-centric approach has been deployed to allow users to gain a holistic perspective of the performance of different fleet configurations across various contexts. The model then calculates KPIs which are then aggregated and weighted to a value metric.

Site simulation approaches

Two different simulation approach has been tested to evaluate their useability and applicability for the quarry and off-road transportation sector, as shown in Figure 1. These two approaches are Discrete-Event Simulation (DES) and Agent-Based Simulation (ABS).

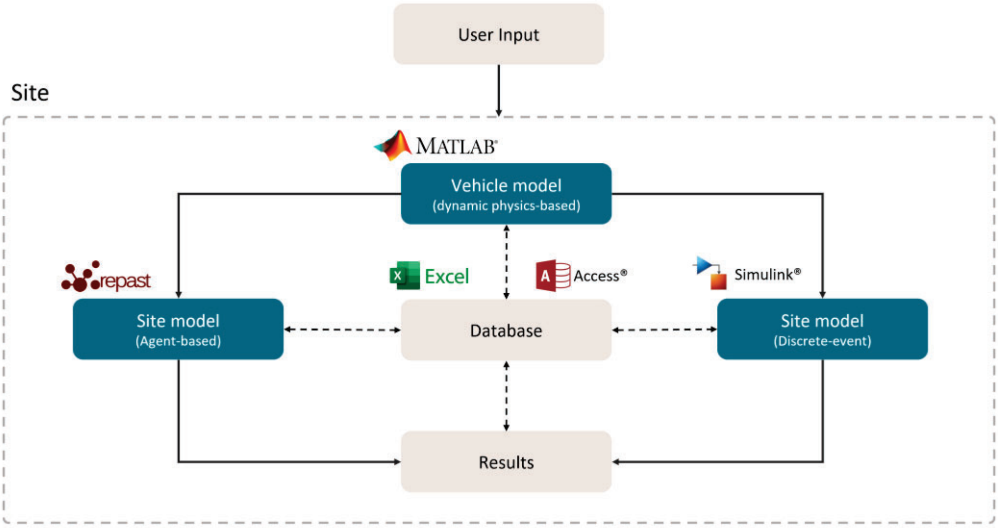


Figure 1: The two simulation approaches used in this project.

Discrete Event Simulation (DES) is a widely used method for modelling operations in construction sites. In DES, each operation is represented as a server that processes entities for a duration typically drawn from a predefined distribution. The operations (servers) are interconnected to modelling the workflow. Traditional methods for creating DES models lack modularity and adaptability, making it challenging to update models to reflect new processes or workflows on-site. To address this limitation, a novel approach to creating DES models has been developed in this project, shown in Figure 2. The approach employs a single, generic server that can be programmed with various service calculation methods and a generic actor (entity) that can be configured to follow different work plans. This modular and dynamic design significantly improves the adaptability of DES models, allowing for easier updates and reconfigurations to reflect evolving site workflows and processes.

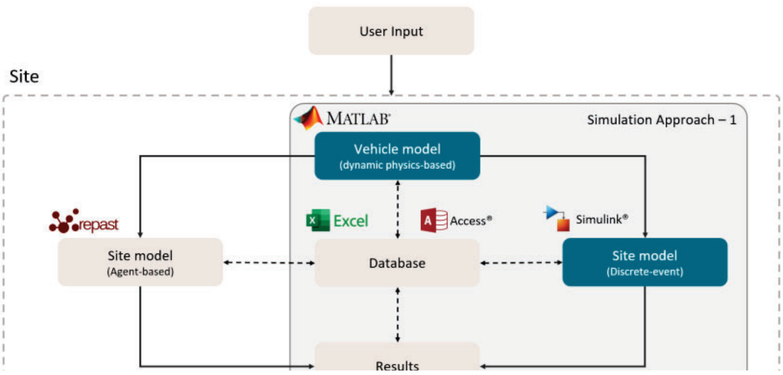


Figure 2: Simulation Approach - 1

In contrast to the DES, the ABS model focuses on modelling the system behaviour. This approach, shown in Figure 3, uses agents that populate a context and then enact a predefined behaviour over the simulation time. Agents can be seen as systems in a quarry operation, such as haulers, wheel loaders, and crushers. Each agent has a programmed behaviour that should resemble the real-world behaviour as closely as possible. This means that ABS models are, in contrast to DES, generic from the start but require large development efforts. The flexibility to shift work plans and operational schedules is managed by creating a control tower agent that then distributes work tasks to the individual machine agents and monitors the operational performance. Moreover, the machine agents will utilize the developed machine models to get realistic behaviour, e.g., velocity and energy consumption. The ABS model has been developed using the open-source software RePast (https://repast.github.io/).

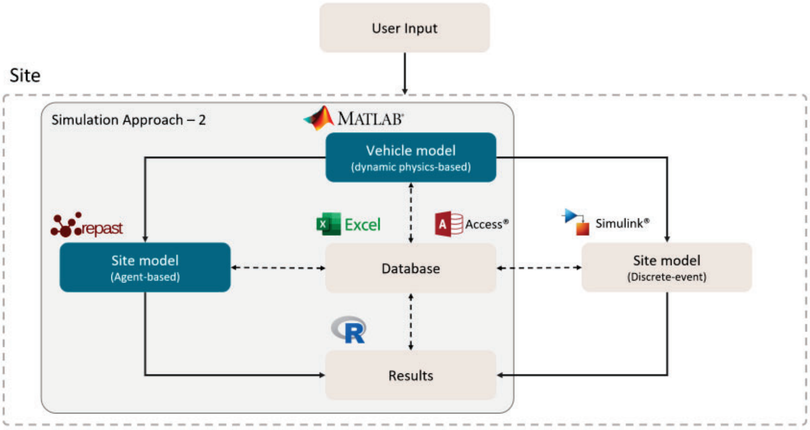


Figure 3: Simulation Approach - 2

Visualization model

Once a site has been simulated, it is essential to visualize the scenario to analyse the results. The visualization model is constructed using two approaches: basic and advanced. A key is that both visualization techniques use the same dataset. Thus, users may choose a visualization approach based on their preferences at the cost of rendering time.

Based on the user's selection, the basic visualization model first plots the site route with the elevation profile. Then, it uses a scatter plot animation to visualize the instantaneous positions of load receivers over time dynamically, refer to Figure 4. Users can control the playback speed, pause, restart, and select specific segments of the simulation. Furthermore, the application can visualize data associated with simulation and offers a geo-plotting mode, enabling users to view the site on a 2D representation of Earth, similar to Google Earth. Also, the user can use the geo-plotting mode to edit the operational scenario, allowing for plugging in different machines as shown in Figure 5. Despite being rather simple, it allows users to quickly glance at the results and see how the fleet would operate. This visualization was done using MATLAB.

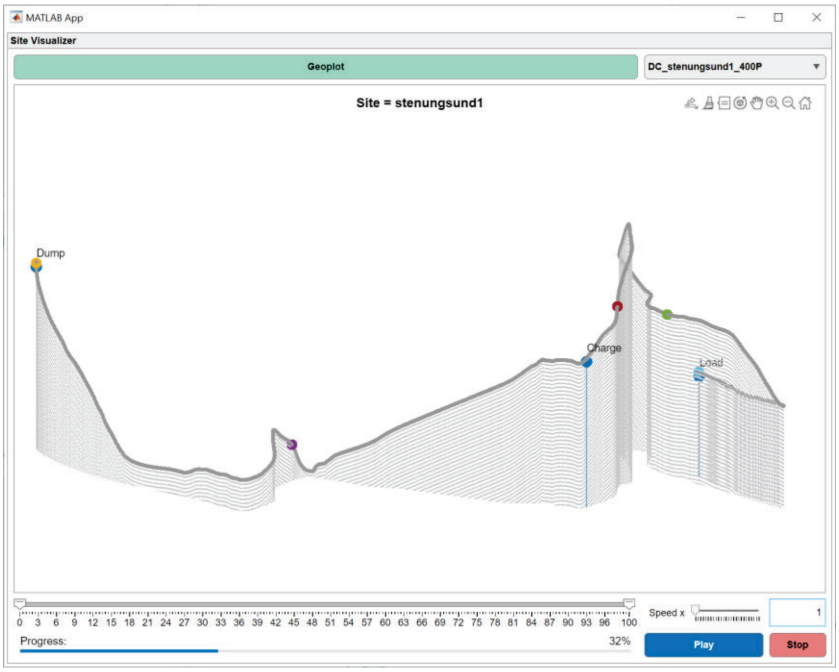


Figure 4: Basic visualization setup

Figure 5: Visualization in geo-plotting mode

The second, more advanced option is to utilize game engines to visualize the results. This has been developed using Unity (https://unity.com/) and Unreal Engine (https://www.unrealengine.com/) and is based using the same principles as the basic visualization. The motivation for using two different game engines was to test their capabilities and suitability as a module in the proposed architecture. It was found that both options work equally well. A prerequisite for this visualization model is that 3D site scans are available to represent the environment. Also, some manual work is necessary for the visualization to work as desired. Once set, the user can import and overlay multiple simulations in one operational scenario, enabling them to compare different solutions. The simulation can be visualized on monitors as well as VR headsets to obtain a more immersive experience. Figure 6 shows a snapshot of Site A rendered in Unity, while Figure 7 visualizes the rendering of Site B in Unreal Engine.

Figure 6: Site A in Unity

Figure 7: Site B in Unreal

5.1.4 WP4 Machine Optimisation

All the machine models were developed using the principles of model-based systems engineering. These models were the core of DES or ABS simulations, especially when a relatively higher fidelity level simulation of a vehicle was desired. The vehicle platform was modular at all system levels. This allowed for the flexible combination of various subsystems to construct a wide range of machines, including those not yet developed. Based on the selection of the baseline model, the user can build a variety of configurations further. These configurations were subjected to different constraints, ensuring each machine's selection of realistic and suitable subsystem options. These subsystems include engines, motors, gearboxes, batteries, etc. Once a vehicle configuration is defined, it is simulated within the operational scenario. The performance analysis of a vehicle can be performed using three different approaches: average-point, quasistatic, and dynamic. The average-point approach is an over-simplification of the system at a single operating point, i.e., a total average over the entire work task. In the quasistatic approach, the trajectory is discretized into small segments, and the dynamics are assumed to be in instantaneous equilibrium between every discretized point. Hence, it is necessary that the discretization is reasonably small. Also, no transient effects like inertia or delays are considered. Finally, the dynamic approach involves using ordinary differential equations to model the complex dynamics of the propulsion system, requiring higher computational effort. Considering the trade-off between accuracy and computational effort, the quasistatic approach was selected for analysis. Point-mass and single-track models were developed to assess vehicle response. In point-mass models, the entire vehicle mass is assumed to be concentrated at a single point. These models capture energy consumption while keeping the computation cost significantly low. Single-track models consist of two tyres, one for the front axle and one for the rear axle. They allow capturing cornering responses in addition to energy consumption at the cost of computational effort. The setup of the simulation can be forward or backward facing depending on the requirements. Forward models begin with the engine's power output and simulate its distribution to the wheels. Conversely, backward models start at wheels, calculate the total force required to move the vehicle, and subsequently determine the necessary engine power. Both these approaches are commonly used as they offer different advantages. One of the key differences is whether velocity is considered a dynamic state. If so, then the model is intrinsically forward. The forward model is a system of differential-algebraic equations that are solved to calculate the new velocity based on the control inputs and current velocity. Such models are ideal for analysing the influence of environmental factors. Hence, a forward-facing setup was used to simulate the vehicle since the requirement was to find an optimal velocity for a given trajectory in the site.

Optimisation aims to identify the "best" solution within specific constraints. In the case of engineering design, several different optimisation techniques and algorithms can be used to achieve this. One of the key requirements is to integrate system design variables, state variables, control policies, and contextual variables into an optimisation problem to accommodate diverse operational strategies. A dual-layer framework was proposed to support the development teams. Figure 8 shows the dual-layer optimisation approach where a multi-objective problem is solved to obtain tradespaces. Tradespaces map design attributes against desired objectives, highlighting the sensitivity of a certain design variable to fulfil the needs. The design variables configure a viable machine based on the defined constraint, the state variables are the responses of that machine, control policies are the sequences of control inputs that enable the machine to accomplish an operational task optimally, and contextual variables are all the aspects that can influence the value of the machine, such as road conditions, ambient temperature, etc. Depending on the number of objectives, a multi-attribute tradespace highlighting the Pareto can be extracted using this approach. Solutions lying on the Pareto Front are all non-dominated designs.

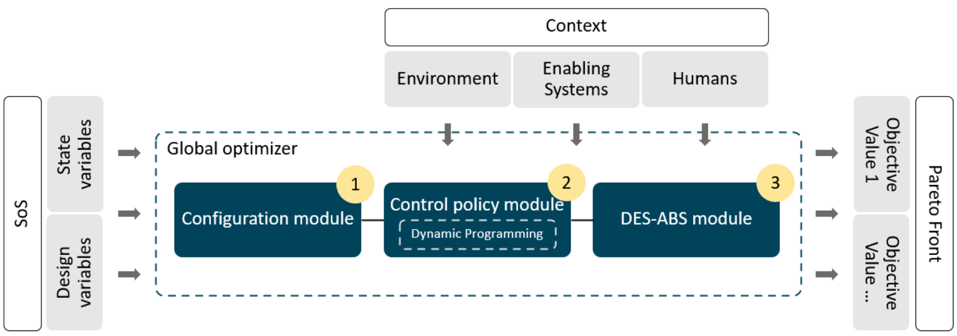


Figure 8: The dual-layer optimisation architecture for tradespace exploration.

To demonstrate this approach, an optimisation problem of a fleet of electric haulers was considered. The operational scenario was a quarry subjected to many contextual changes. Material production rate, fixed cost, and operational cost were the three objectives for exploring the tradespace. Figure 9 shows a tradespaces from one such optimisation run. The grey dots indicate the dominant designs from the last 50 generations of the optimizer. The fuzzy Pareto front was selected using a surface built via regression. These tradespaces are a combined mapping of configuration variables and control policies. Views A, B, and C have been presented in Figure 9 to compare two objectives at a time. In View C, “n” represents the number of machines in the fleet. Several inferences can be made from such tradespaces. For example, view C shows that the fixed cost exhibits a strong positive correlation with “n”, while the operational cost does not necessarily follow the same trend. Views A and B show that the quarry maxes out productivity at a certain threshold. No further addition of machines could increase productivity unless some other aspects are changed. Also, three exemplary points, highlighted in red, yellow, and green, illustrate the decision-making process regarding the optimal fleet configuration. Design Red represents a single hauler with a 30-ton payload and a 50kWh battery. Design Green comprises a fleet of two haulers with 10-ton payloads, 50kWh and 20kWh batteries respectively. Design Yellow is identical to Design Red, but it is driven in a time-efficient manner. It can be inferred that although Design Green incurs higher investment costs than Design Red, it surpasses Design Red in both material production rate and operational cost. Furthermore, despite the productivity increase in Design Yellow, Design Green could still be a more favourable option due to its lower overall investment.

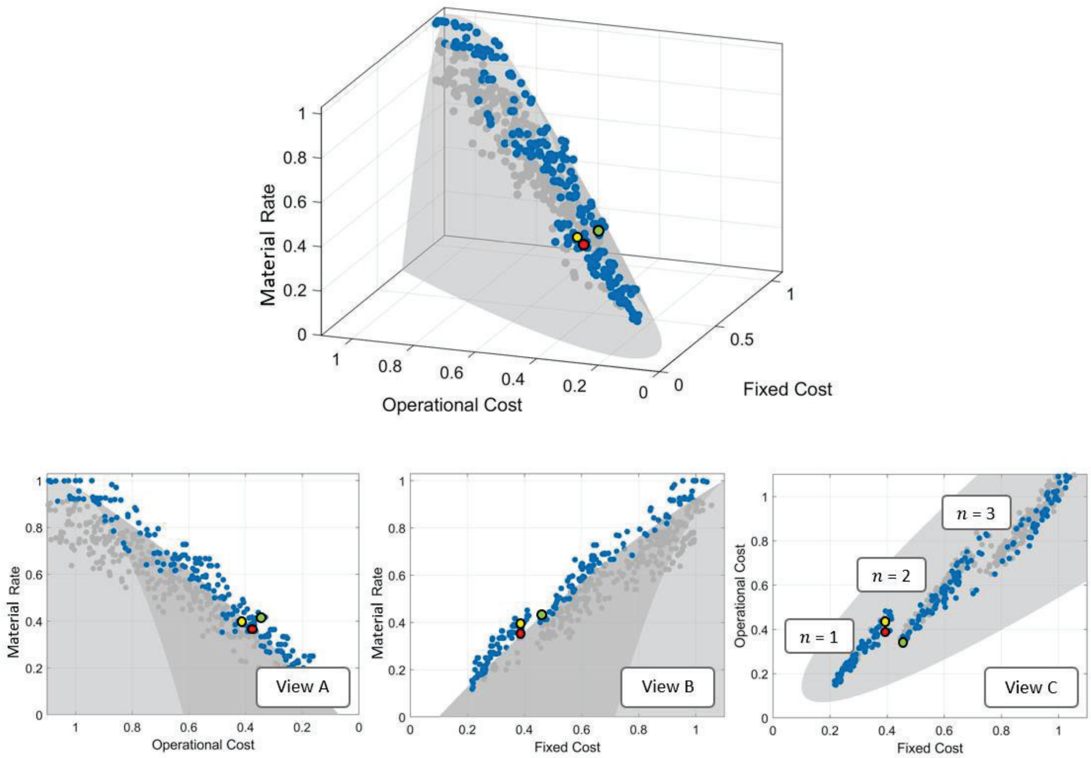


Figure 9: Exemplary tradespace explored using the dual-layer optimisation architecture.

The tradespaces were populated by simultaneously mapping the configuration and control variables. More precisely, the state transitions observed in DES or ABS simulations were derived by an optimal control policy for each machine. An optimal control policy is basically a sequence of instructions that decide how a system should behave over time to achieve a specific objective. In the case of haulers, it would be choosing the most appropriate set of actions in terms of accelerating, braking, steering, changing gears, etc., at each step to navigate to the destination efficiently. The term efficiently implies fulfilling the defined criteria, such as minimizing fuel consumption, minimizing time, minimizing speed fluctuations, etc. Different techniques have been used for haulers (load receivers) and wheel loaders (load carriers), elaborated as follows:

Optimal control policy for the load receivers
Dynamic programming (DP) was used to calculate the optimal control policy for the load receivers. DP offers many advantages for solving complex optimal control problems by decomposing them into smaller, more manageable subproblems. It ensures optimality by considering all possible combinations to construct the overall solution. Also, DP is versatile to include a mix of discrete and continuous variables, such as integrating gear shifts with vehicle speed.

During tradespace exploration, DP determined the optimal velocity profile through an optimal control policy. This optimality was achieved by striking a balance between energy consumption with the time required to complete the desired task, such as transporting a payload from point A to point B for a hauler. From a user perspective, this can be referred to as Eco driving vs Speed driving. The control policy acts as a decision-making rule, guiding the actions of the vehicle based on its current state (e.g., location, battery level, payload). Figure 10 shows how a different balance between energy consumption and time required to complete a task can render a different control policy, denoted by solid (speed-driving) and dashed lines (eco-driving). Aggregated results of applying such a policy were fed to DES or ABS simulations that allowed a change in the system's state as the simulation progressed.

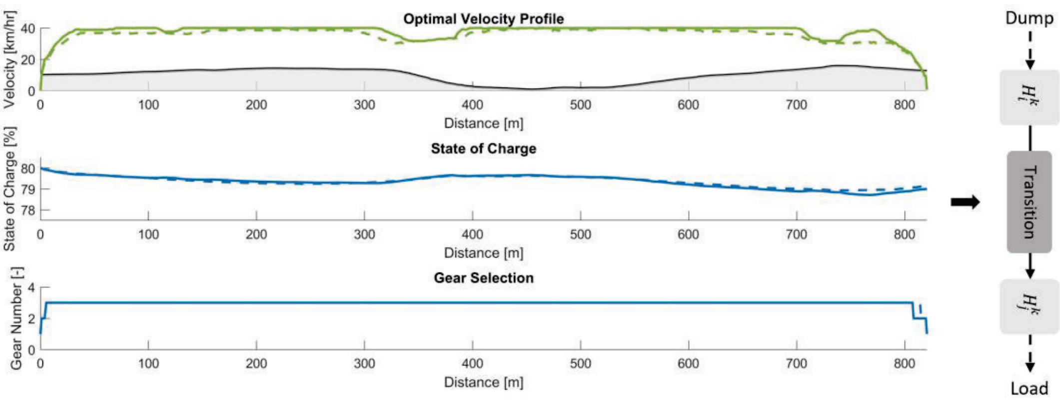


Figure 10: Different time penalty values affecting the optimal velocity profile.

Optimal control policy for the load carriers
DP offers a powerful framework for solving a wide array of control problems. They excel in problems that have a finite horizon and relatively lower state and action space. However, as the number of states and control inputs increase, the computational complexity of DP grows significantly, making it intractable for many real-world problems. Also, DP necessitates a precise model of the environment, limiting its effectiveness in scenarios with uncertainty and stochasticity. Reinforcement Learning (RL) is a promising alternative that provides a practical approach to control policy optimisation in such high-dimensional and uncertain environments. Given the interplay between DP and RL, a hybrid approach selectively utilizing the strengths of each of these methods can be worthwhile for certain types of optimal control problems. Thus, a combination of DP and RL was used to calculate the optimal control policy for the load carriers.

Essentially, the idea is to decompose the task into several subtasks and choose either DP or RL to solve the subtask. As explained, the choice of DP or RL depends on the complexity of the problem and the availability of a reliable model of the environment. For the case of the loader carriers, the tasks assigned to the wheel loader can be divided into four phases: transport without load, loading, transport with load, and unloading. These phases essentially form the subtasks that shall be solved either with DP or RL to calculate the optimal control policy. Transporting with or without load is a finite-horizon problem. Also, these subtasks have predictable dynamics because the machine and terrain are known beforehand. Thus, DP can be an effective method to obtain the optimal control policy for this subtask. On the other hand, loading the attachment involves interacting with a pile that can exhibit highly non-linear behaviour and stochasticity. Also, the policies must generalize across varying gravel piles. Thus, RL can be a worthwhile choice in this case. Once these solution methods (DP or RL) are assigned, specific algorithms within these methods can be employed. For instance, DP may be used in a deterministic form while a wide range of algorithms, including Q-learning, State-Action-Reward-State-Action (SARSA), Deep Q-Network (DQN), Deep Deterministic Policy Gradient (DDPG), Proximal Policy Optimisation (PPO), etc., can be considered for RL.

An optimal trajectory must be planned considering the hauler's location and the pile's location based on machine specifications. A trajectory that minimizes the distance between these two points shall truly minimize energy consumption under conditions where no elevation is considered. With the turning radius limit of the configured machine, a script was developed to determine the shortest path using the Reeds-Shepp algorithm. Figure 11 shows the optimal trajectory calculated for an arbitrary pile and hauler location. Such trajectories were subsequently discretized and projected onto the elevation profile, thus forming the horizon for the DP problem. In the future, this approach can also be expanded to solve "free moving" tasks at other locations in a quarry or mine.

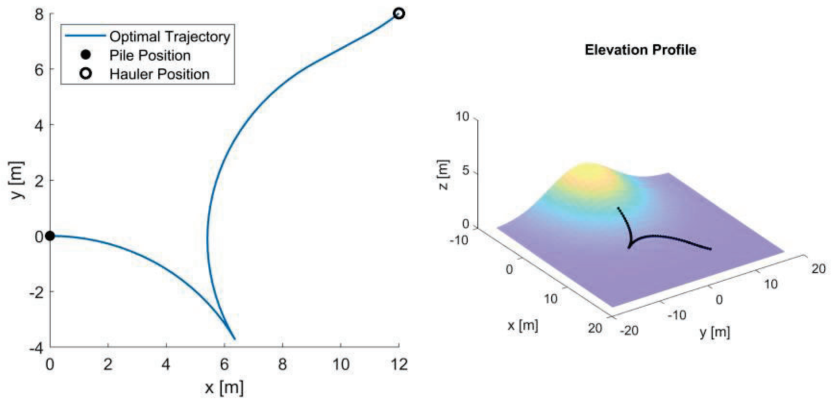


Figure 11: Optimal trajectory calculated from arbitrary hauler and pile location.

Concerning the interaction with the pile, the Fundamental Equation of the Earth-Moving model was used. It is a mathematical model which describes the forces involved in penetrating the pile with an attachment. The process of pile separation, involving the breaking and displacement of pile particles, was modelled based on an idealized scenario of a flat blade moving in the pile. While advanced methods like the discrete particle method exist, they often tend to be intractable. The scooped material was calculated by numerical integration of the path traced by the tip of the attachment. A Double Deep Q-Network algorithm was used to learn optimal attachment-pile interactions. The hyperparameters were meticulously tuned until satisfactory results were achieved.

Figure 12 shows the optimal control policy for an arbitrary wheel loader with the subtasks combined. As shown, the subtask of transport without load was first performed, where DP evaluated the optimal velocity profile for moving from the hauler's position to the pile. The trained RL agent then interacted with the pile to fill the attachment. Exemplary interactions of the attachment with the pile have been shown in the top-right of Figure 12. The corresponding forces acting on the attachment have also been plotted as a function of time in the bottom-right of Figure 12. On completing the interaction with the pile, the wheel loader reversed and reached the hauler's position. Again, DP evaluated the optimal velocity profile. All the other relevant states of the wheel loader have been shown in Figure 12. Analogous to the hauler, aggregated results of applying such a policy were fed to DES or ABS simulations that allowed a change in the system's state as the simulation progressed.

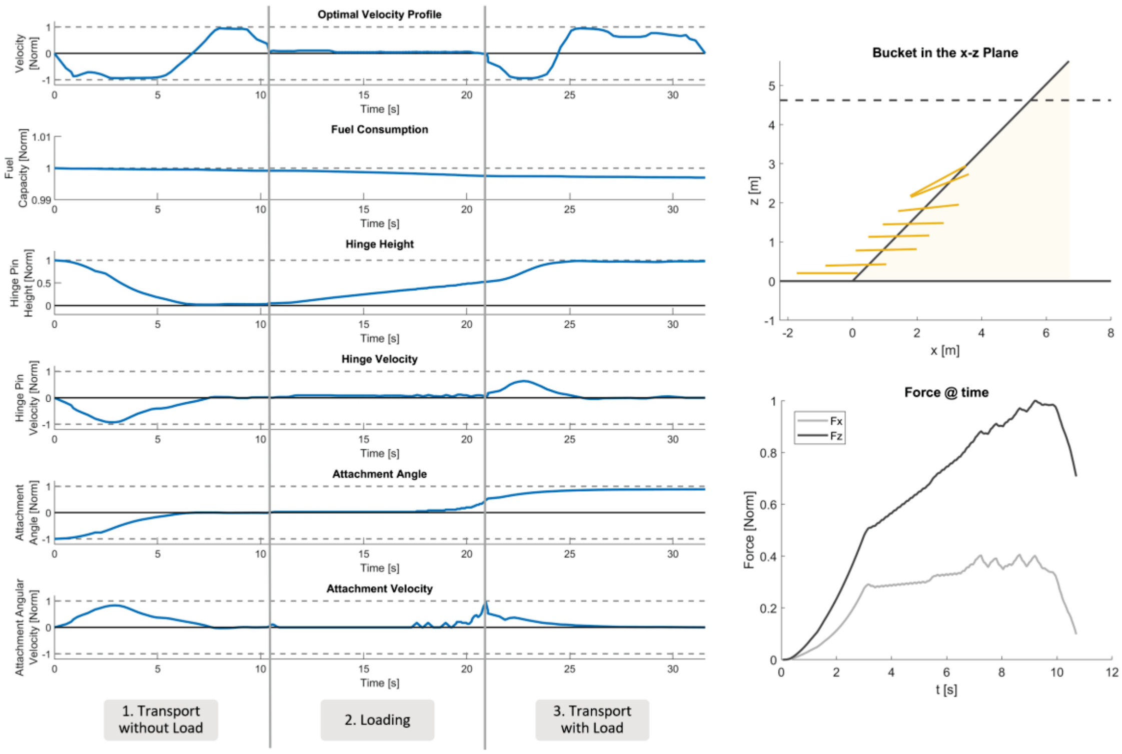


Figure 12: The optimal control policy for an arbitrary wheel loader.

Value-Robust Solution

A significant challenge while using the many optimisation techniques is that it results in statically optimal solutions. Meaning, these optimal designs quickly become suboptimal as the operating context evolves. The mining scenario is poised with rapidly emerging technologies and dynamic contextual factors. Thus, the decision-making process is quite complex for development teams as competing aspects must be traded to achieve higher value. The goal is rather to develop value-robust solutions that can deliver the expected value. From an optimisation perspective, this translates to finding solutions that are feasible and "nearly optimal" under all possible realizations of the uncertainties. While this approach shares similarities with robust optimisation, the key distinction lies in its focus. Rather than optimizing for the worst-case scenarios, it aims at evaluating system performance across dynamic conditions. Thus, the development team can move away from overly conservative solutions toward adaptable and flexible ones that can adjust to evolving conditions.

Tradespace exploration is an essential process in developing value-robust solutions. However, the essence is to arrange these tradespaces in the sequence of evolving conditions. Adapted from Epoch-Era analysis, Figure 13 shows a typical scenario built using multiple epochs and eras. An epoch is a period where the requirements and the context remain fixed. Hence, a tradespace can be used to identify the most valuable solutions. An Era is composed of several epochs, each representing a portion or the entirety of the system's lifespan. An era supports the analysis of both short-term and long-term effects arising from dynamic requirements and contextual changes based on the timespan of an era.

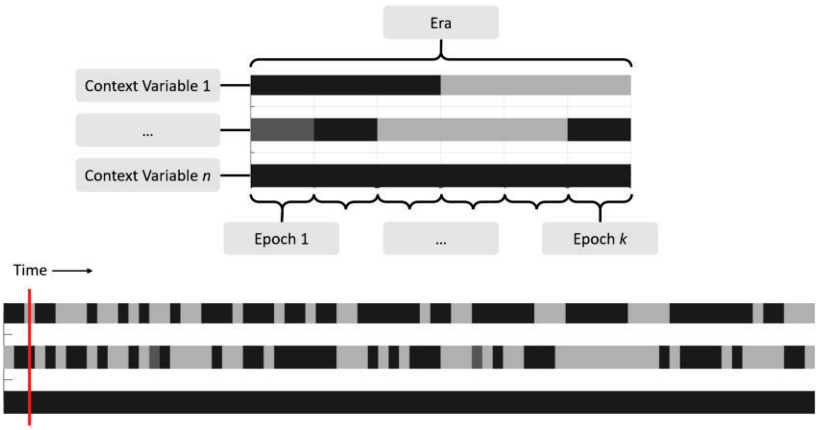


Figure 13: Era construction from multiple epochs

Figure 14 shows the arrangement of the tradespaces along such an era. Such an arrangement can be iteratively performed to identify the solutions that are most promising. The selection of the most promising solution naturally depends on the specific requirements. For instance, a fleet that exceeds the desired material production rate may be less valuable due to overcapacity and the associated investment cost. Tradespaces do not naturally highlight the most valuable solution. Hence, a fuzzy Pareto discretized in clusters is an effective way to select the most valuable solution. As seen in Figure 14, a curve fit is used to extract the fuzzy Pareto front. Additionally, this Pareto is divided into several blocks indicated by vivid colours. A machine learning technique called k-means clustering was employed to get such a discretization. Now, based on the needs, a cluster may be chosen that allows some room for deviations.

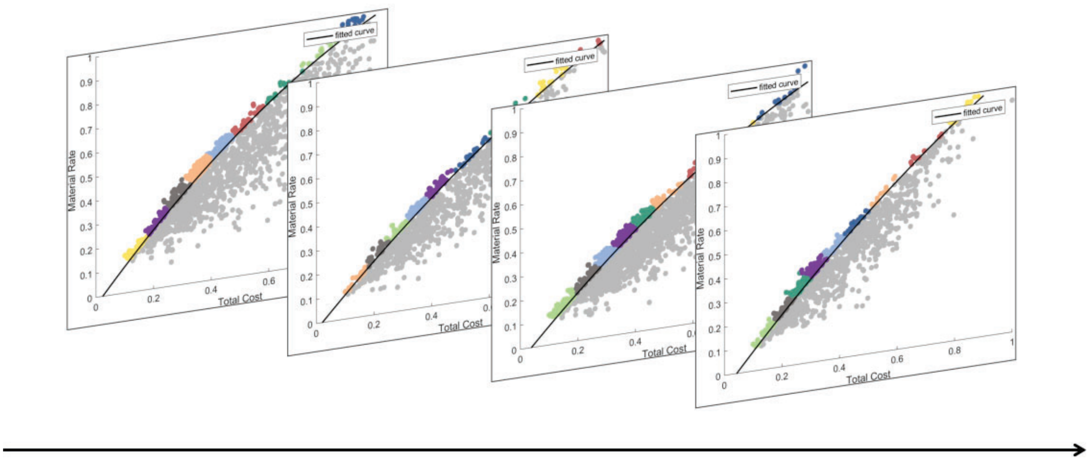


Figure 14: The arrangement of the tradespaces along an era.

Using the same analogy, Figure 15 exemplifies the solution selection process from a tradespace with three attributes, material production rate, fixed cost, and operational cost. The problem addressed involved managing a fluctuating material production rate in changing environmental conditions. A regression surface was utilized to identify the Pareto front, followed by the selection of suitable designs using a clustering algorithm. These designs have been highlighted by yellow. Through an iterative process, the most promising pool of solutions can be selected, ultimately guiding the engineering team towards developing value-robust solutions. This technique is suitable for planning fleet configuration over a longer time span. Also, this approach can be used to develop completely new fleets as well as upgrade existing fleets through the addition of more suitable machines. Furthermore, this technique can provide decision support to equipment manufacturers in deriving the most value-robust designs for vehicles.

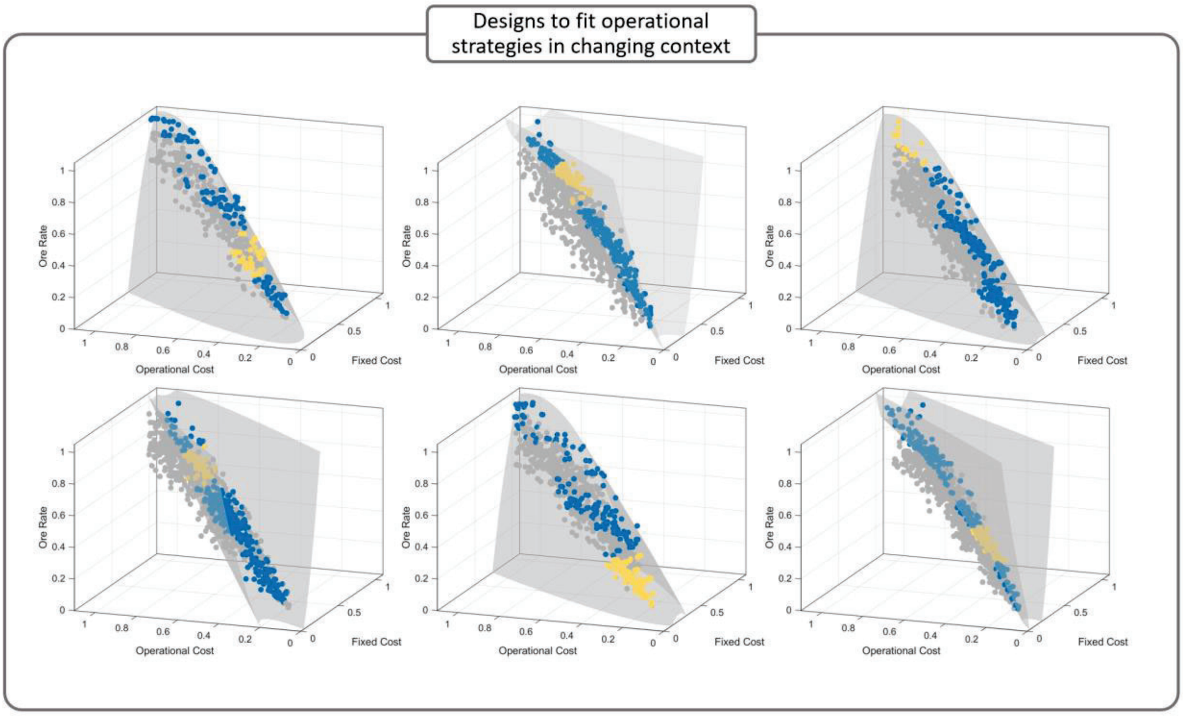


Figure 15: Solution selection process from tradespaces to manage a fluctuating material production rate.

5.1.5 WP5 Site Optimisation

A prerequisite for a good site optimisation tool is accurate modelling of the site, its systems, and operations. WP3 and WP4 describe in more detail how this has been conducted. A generic architecture was established for site optimisation with vehicles and site models. As the site and system models have been previously modelled, this allows for individual calibration of the models. In turn, this means that the trustworthiness of the simulations increases, hence the reliability of the optimisation results. For this project, the site optimisation has been limited to mainly focus on the fleet (load carrier and load receiver) and infrastructure (charging system, mobile/stationary crusher, crusher flow rate). However, the architecture is developed in a modular fashion, allowing more aspects, such as crusher and stockpile locations, to be included in the following iterations.

The general architecture and process of the site optimisation is depicted in Figure 16. It shows how an experiment is set up, executed, and disseminated. The process here comprises five steps, which can be summarized as follows.

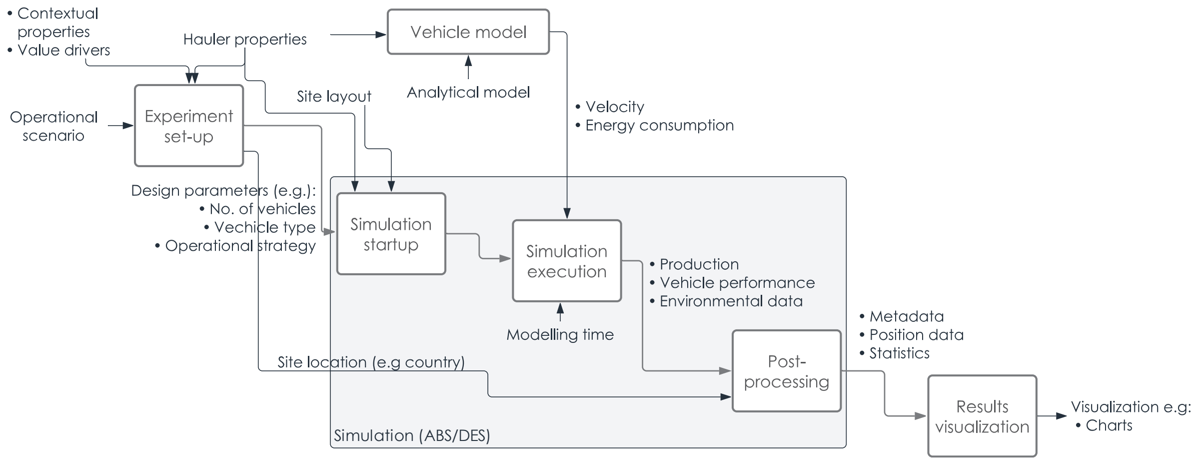


Figure 16: General architecture and process of the site optimisation.

1. **Experiment setup:** The first step is to decide the design parameters that should be used in the simulation, i.e., setting up the design space that is going to be explored. The amount of design parameters is dependent on the context and option availability at hand, but it could, for instance, include the number of vehicles, vehicle type, path selection, operational strategy, etc.
2. **Simulation startup:** The defined design space established in the previous step is then fed into the simulation platform. A design space is a complete space representing a combination of a given set of design parameters where each combination is an operational scenario. The startup process includes populating the model with correct paths, stations, and vehicles. It will also start the vehicle model with the correct settings and prepare it for later execution; in this case, start a MATLAB engine.
3. **Simulation execution and vehicle model:** The heart of the process is the third step when each operational scenario is simulated. Based on the predetermined modelling time, the site model will execute the mining process according to the operational strategy and provided operational scenario. The simulated vehicles in the site model are called the vehicle model as they are assigned new work tasks. This step is iterated until all operational scenarios are simulated and completed.
4. **Post-processing:** Once the design space has been explored, the collected statistics data from each operational scenario, e.g., hauled material, energy consumptions, queueing times, etc., is exported for post-processing, where the data is aggregated to KPIs as well as value and disseminated according to the user needs. Using “raw” simulation data makes it possible to tweak the aggregation methods if the needs or relative importance of the KPIs and value.
5. **Visualizations:** The value metrics for each scenario are accumulated into charts to create a better overview and support for decision-making. Each operational scenario can also be imported into the visualization model for a more immersive experience of how the operation would look like.

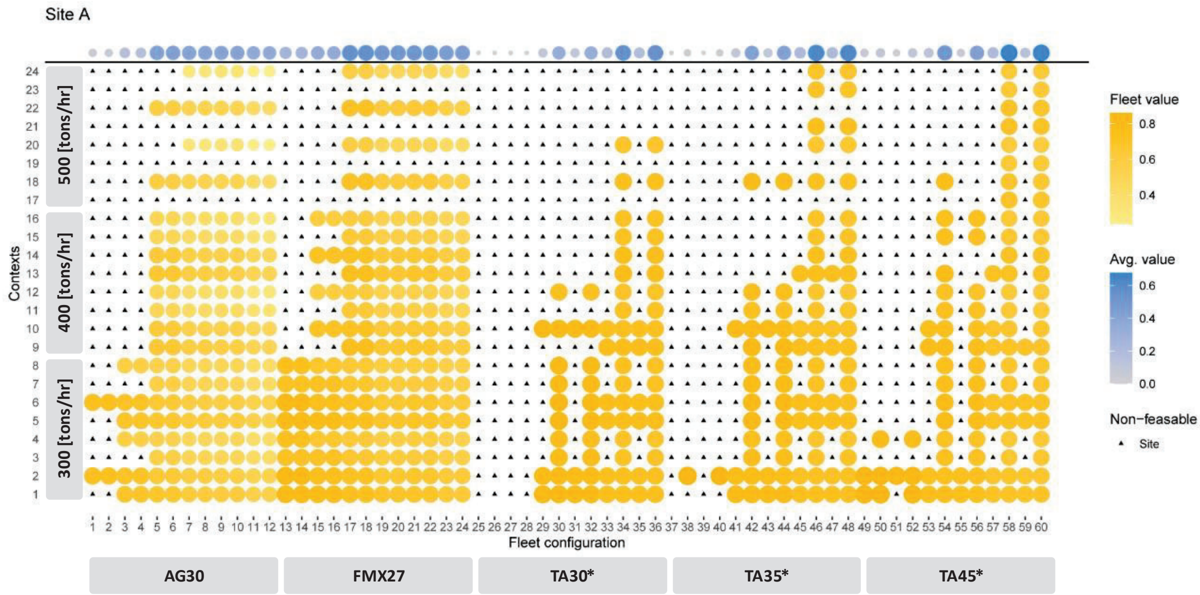
To illustrate this process, a design challenge connected to one of the demo sites was selected, site A. The experiment is to evaluate different hauling machine selections, hauler quantity, driving mode, and number of charging poles. This is complemented with contextual parameters to assess the resilience of each fleet. The contextual design parameters were set to production rate, mobile crusher usage, wheel loader attachment size, and road frictional loss. Table 2 presents all the values for each design parameter that together form the design space.

Table 2: Values for each design parameter forming the design space.

Parameter	Values				
Vehicle configuration	A30	FMX27	TA30*	TA35*	TA45*
No of vehicles [#]	3	5	7		
Driving mode	Eco	Speed			
No of chargers [#]	1	2			
Production rate [tons/hr]	300	400	500		
Mobile crusher [y/n]	Yes	No			
Attachment size [tons]	5	15			
Road friction [-]	0,03	0,05			

*Non-existing machines that are virtually scaled from TA15.

The result from this exercise is visualized in a bubble plot, see Figure 17. The bubble plot shows the overall value creation at each operational scenario (yellow bubbles) as well as the fleet value (blue bubbles). The x-axis lists all the fleet configurations, while the y-axis lists the different operational contexts. The size and colour intensity of the bubbles indicate the value. This plot allows user or stakeholders to quickly get an overview of the feasible configurations and their value creation. By summarizing the value for each fleet across all contexts, it is possible to get a perception of the value robustness. This allows users to determine which fleet that performs the best across the contextual variations and thus minimizing the risk of optimizing the fleet selection toward a single operational context.



*Non-existing machines that are virtually scaled from TA15.

Figure 17: Bubble plot showing the value creation at each operational scenario

To make a more detailed comparison, select the top six fleets and create a chart plot visualizing the cost, sustainability, utilization, and total value. See Figure 18. The fleet configuration of each run is documented in Table 3. The chart supports the user to see how the value for a fleet configuration is achieved through its performance in the three different value drivers, here defined as cost, sustainability, and utilization but can be changed depending on the user's need. This is just an example of how the site optimisation model can be used as a decision-support tool where an explorative approach is taken.

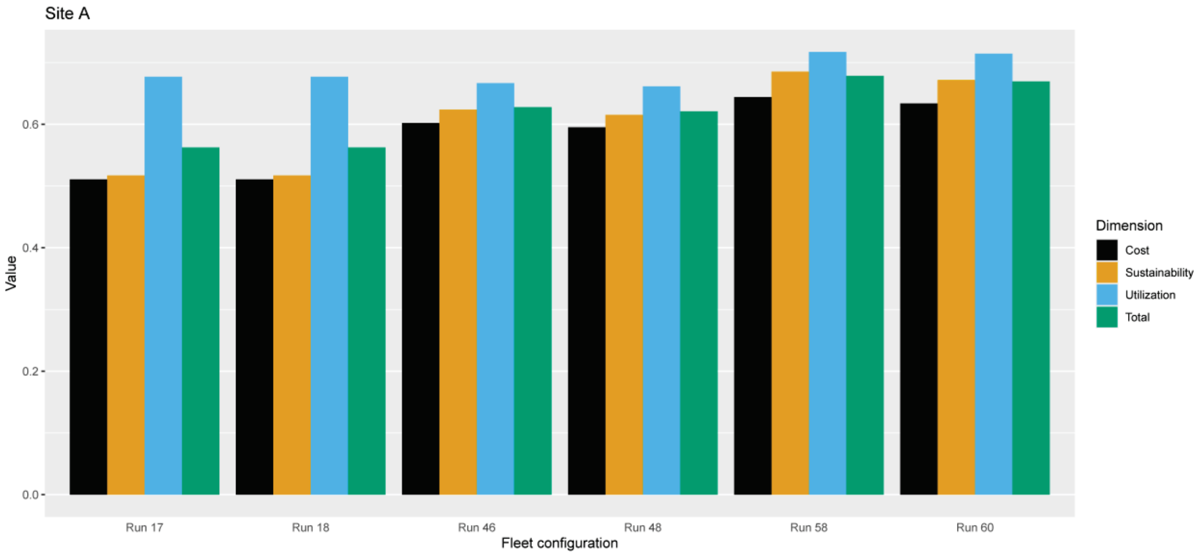


Figure 18: Bar chart showing different KPIs for the top six performing fleets.

Table 3: Configuration of the top six performing fleets.

Simulation	Vehicle type	No of vehicles	Driving mode	No of chargers
Run 17	FMX27	5	Eco	1
Run 18	FMX27	5	Eco	1
Run 46	TA35*	7	Speed	2
Run 48	TA35*	7	Speed	2
Run 58	TA45*	7	Speed	2
Run 60	TA45*	7	Speed	2

*Non-existing machines that are virtually scaled from TA15.

These results show that the developed simulation platform can support decision-making by simulating and assessing a large variety of design configurations at a relatively low effort. The flexible and scalable characteristics of the simulation platform provide site optimisation with the ability to test and evaluate any operational scenario without the need for user interventions. Furthermore, the value exploration perspectives allow the user to investigate and better understand how different values are impacted by certain design options and, instead of looking at each performance metric in isolation, obtain a holistic view of value. Even though the site optimisation and simulation platform can be further developed, this Proof of Concept illustrates the potential in off-road transportation and mining operation optimisation.

5.1.6 WP6 Digitalized Services

From an industry perspective, stepwise implementation is important, partly due to “trust of the virtual support tools” and partly due to willingness to change and adaptiveness.

This work package successfully delivered key advancements in the identification and definition of digitalized services and the development of suitable business models.

Dynamic capabilities for digital servitisation

Understanding the capabilities required to transition from traditional services to digitalized services is crucial. To explore this transition, dynamic capabilities (DC) theory has been employed as a framework to identify the specific capabilities relevant to traditional servitisation and those necessary for digital servitisation. Dynamic capabilities encompass three core elements: sensing, seizing, and reconfiguring capabilities. Sensing capabilities refer to a firm's ability to detect and shape new technological and market opportunities while also identifying potential threats. Seizing capabilities, on the other hand, involve the firm's capacity to respond to these opportunities by developing new services, safeguarding their innovations, and leveraging emerging possibilities. Lastly, reconfiguring capabilities pertain to the firm's ability to reorganize and adapt its resources, processes, and operational skills to align its internal functions with the opportunities it has seized.

In our research, we have identified specific microfoundations for each of these dynamic capabilities — sensing, seizing, and reconfiguring. As shown in the below figure, for traditional servitisation, 11 microfoundations have been identified, and for digital servitisation, another 11 microfoundations are recognized, as shown in Figure 19. Furthermore, our findings reveal three significant challenges that must be addressed to build dynamic capabilities for traditional servitisation. Simultaneously, we have identified five critical enablers that facilitate the development of dynamic capabilities for digital servitisation, which can help overcome these challenges. Based on these insights, we propose an integrated framework of dynamic capabilities necessary for navigating the transition from traditional servitisation to digital servitisation. This framework provides companies with a comprehensive understanding of the dynamic capabilities and microfoundations required to ensure a smooth and successful transition. By addressing the challenges and leveraging the enablers identified in our work, companies can better prepare themselves to thrive in the evolving landscape of digitalized services.

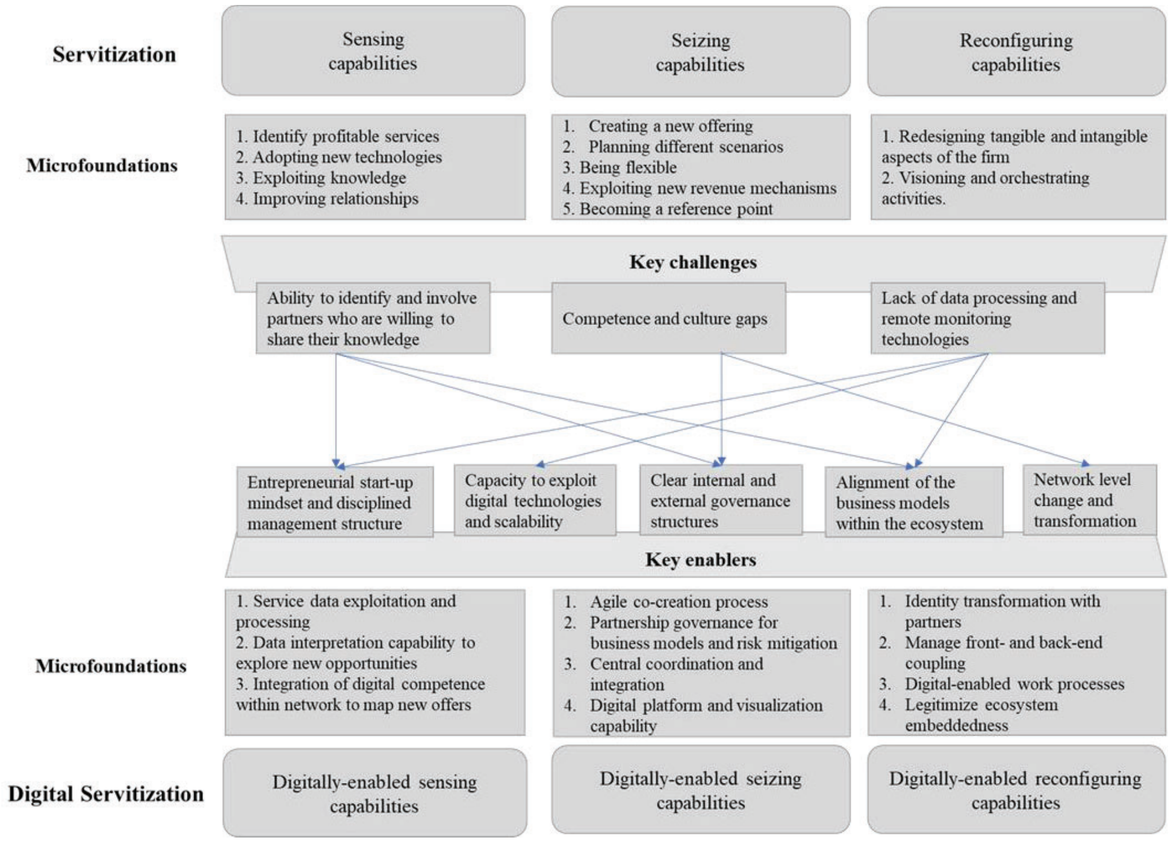


Figure 19: Mircofoundations identified for traditional and digital servitisation.

Construction site levels and digital micro-service types

Building on this understanding of the microfoundations of dynamic capabilities (DCs), as well as the key challenges and enablers, the process of identifying and mapping potential types of digitalized services and exploring various possible service scenarios has commenced. To facilitate this investigation, the construction site was conceptualized into four distinct service levels: site, fleet, machine, and component levels, as illustrated in the figure below. This conceptualization provided the foundation for identifying potential digital micro-service scenarios tailored to each level, as showing in Figure 20.

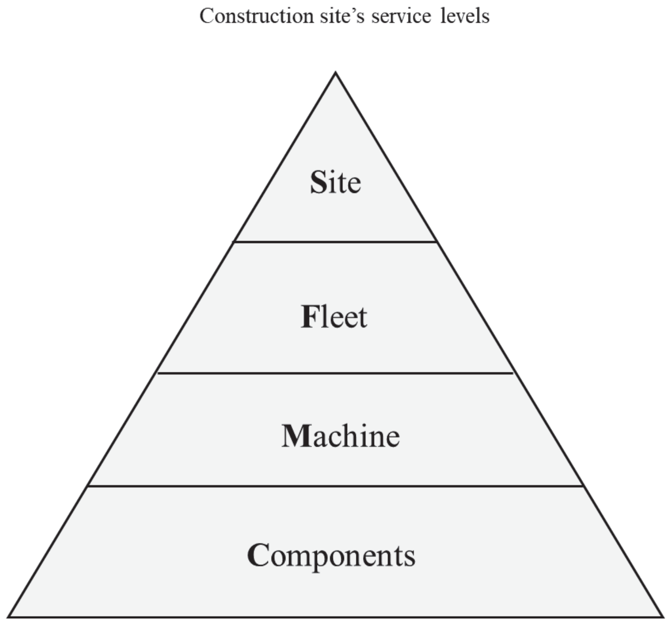


Figure 20: Pyramid showing the service levels

The decision to investigate from a micro-service perspective stem from the advantages it offers in addressing complex and dynamic environments, such as construction sites. Micro-services allow for greater flexibility, scalability, and customization at each service level. By focusing on specific, well-defined scenarios, micro-services facilitate the development of targeted, efficient solutions that can adapt to varying needs and technological advancements. A service, in this context, refers to a broad set of activities or solutions designed to meet specific customer or operational needs, often encompassing a wide scope and impacting multiple areas of functionality. A micro-service, on the other hand, is a more granular and specialized solution that targets a specific functionality or problem area. Micro-services are modular, independently deployable components that collectively form a more comprehensive service architecture. Together, these benefits position micro-services as a powerful approach to achieving operational optimisation.

For each service level, **specific micro-service scenarios** were defined to address unique challenges and opportunities. For example, at the site level, three scenarios were identified: zero-emission site design, sustainable site material flow, and overall site energy management. Similarly, at the machine level, three scenarios were outlined, including providing machine performance information, optimizing machine use for various stakeholders, segment customization, and predictive maintenance for cost-effective operations. These targeted solutions highlight how a micro-service approach can enable tailored and impactful digital innovations across multiple levels of construction site operations.

Building on this foundation, **six types of digital micro-services** were proposed, encompassing *planning-oriented, productivity-related, maintenance-related, sustainability-oriented, infrastructure-based, and consultancy-related services*. Each category reflects a distinct focus area, addressing critical aspects of construction site operations. Within these six categories, two additional subcategories of micro-services were introduced to offer more specialized solutions tailored to specific needs. To streamline implementation, a guiding matrix was developed as shown in Table 4, linking the six types of micro-services to the four service levels of the construction site: site, fleet, machine, and component. This matrix serves as a strategic tool, enabling a structured approach to identifying and deploying appropriate micro-services at each level. By aligning service categories with specific operational contexts, the matrix supports a comprehensive and adaptable framework for digital transformation in construction site management.

Future development pathways for digital micro-services for the company were also identified, spanning 3-, 5-, and 10-year horizons. Scenario-based insights were generated, considering the technological, organizational, and market factors that influence the successful adoption and scalability of these services.

Table 4: Guiding matrix linking the micro-services to the service levels.

Service levels/ Types of micro-services	**Planning-oriented**	**Productivity-related**	**Maintenance-related**	**Sustainability-oriented**	**Infrastructure-based**	**Consultancy-related**
Site						
Fleet						
Machine						
Component						

Key challenges and coping strategies to implement digital micro-services

The analysis identified critical challenges and corresponding coping strategies essential for successfully implementing digital micro-services across the service levels of a construction site. These findings were organized using the Technological-Organizational-Environmental (TOE) framework, which provides a structured approach to understanding the complexities of digital transformation.

A total of 12 key challenges were identified, including application intricacy, data aggregation issues, balancing platform simplicity with accuracy, small team size, mastering user value, crafting an effective go-to-market strategy, ensuring process clarity, managing external dependencies, maintaining resource resilience, refining target audience strategies, addressing customer willingness to pay, and achieving internal-external harmony.

To address these challenges, specific coping strategies were proposed. These include simplifying application development, improving data management practices, optimizing the balance between platform usability and accuracy, leveraging the strengths of small teams, mastering customer value delivery, refining go-to-market approaches, clarifying operational processes, minimizing external dependencies, enhancing resource management, precisely targeting customer needs, and aligning internal goals with external demands.

To facilitate practical implementation, a guiding framework was developed in the form of a matrix, as shown in Table 5. This matrix links the identified challenges and coping strategies to the service levels of the construction site and the relevant dimensions of the TOE framework. By offering a clear and actionable structure, the framework supports organizations in navigating the complexities of digital micro-service implementation and achieving sustainable outcomes.

Table 5: Matrix linking the identified challenges and coping strategies to the service levels

Service levels / TOE-related challenges & strategies	**Technological-related key challenges & coping strategies**	**Organizational- related key challenges & coping strategies**	**Environmental- related key challenges & coping strategies**
Site	Key challenge 1 -Coping strategy 1 -Coping strategy 2		
Fleet			
Machine			
Component			

During this research project the industrial part have built confidence and competence to move into the area of services around fleet- and site optimisation at a deeper level than before, e.g. “Site optimisation” that will be launched during spring, much due to the knowledge build in projects like this.

5.1.7 WP7 Demonstration

The overarching purpose of the project was to create customer value by raising the level of trusted decision support tools and to support increased levels of servitisation through a modular approach. As the project progressed, the level of complexity of moving to a data driven approach for modelling and simulating the entire operations led to the need for a few simplifications. The decision on these simplifications were taken with customer value in mind and as the main priority. This allowed for a focus to push the simulation architecture and the essential models as far as possible within the scope of the project with maintained customer benefits and servitisation outcome.

First, a decision was taken to focus the project work on simulation of the main site work tasks, representing most of the impact on site performance. Secondary work tasks are more complex to model and represent a much smaller part of site performance impact and were for the moment left out. However, due to the modular nature of the framework, these can be added at a later stage if needed.

A second simplification was also decided to allow for more extensive work on modelling and the simulation framework. Also, due to the repetitive nature of the site operations and the input data provided by NCC, a shorter period of data collection was carried out, which was then extrapolated to represent a longer time-series of data. A longer period of data collection would have provided little extra value to the project and the customer and would have reduced the efforts possible in developing the framework.

In addition, the project faced challenges in accessing real-time data from the equipment on site, resulting in a focus on off-line validation and verification instead.

Instead, and additional to the original project plan, it was decided to use two quarries in the project: Site A to develop the models and Site B for validation, verification and demonstration. This helped the project to focus on modularity and not building site-specific solutions.

As a part of the demonstration, a basic user interface and simulation execution app was developed. The developed simulation modules and machines/system models serve as a base platform for running the optimisation and design experiments, but setting up and running the simulations needs to be supported to be more user-friendly. As a result, a basic app was developed to set up, run, and visualize the operational scenarios and design experiments. Figure 21 illustrates the general architecture and interaction between the different layers and the app. This setup provides a generic integration where the app can be refined to cater to specific user needs.

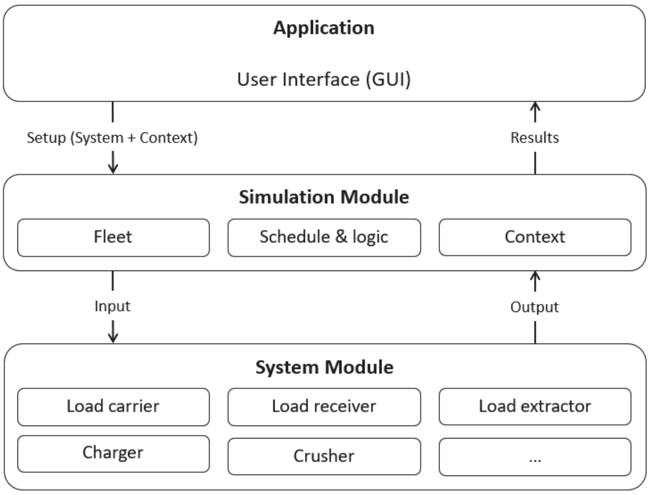


Figure 21: The general architecture and interaction between the different layers and the app

Three different perspectives were added to the user interface as they were realized as the needs of such a tool: Evaluate, Explore, and Exploit. These three perspectives are shown in Figure 22, Figure 23 and Figure 24, respectively.

The first perspective is the Evaluate tab, intended for a detailed investigation of a single operational scenario. This is mainly for users to better understand better assess how a specific scenario performs and compare the current state with the potential optimum. The second perspective, Explore, allows the user to configure a design space that the app will then sweep to identify the KPIs and value creation for each of the operational scenarios. This can be used to assess different fleet configurations and their resilience to contextual changes. Finally, Exploit leaves the optimisation to the app, where a design space comprising several different configurations and control parameters is leveraged to iteratively build viable solutions and test them in a dynamic context. It further incorporates Epoch-Era analysis to understand the lifecycle value of a solution. Together, these three perspectives showcase the versatility of the developed simulation platform. Thanks to the modularity and multi-layered approach, it is possible to easily create different perspectives and expand the app depending on future needs.

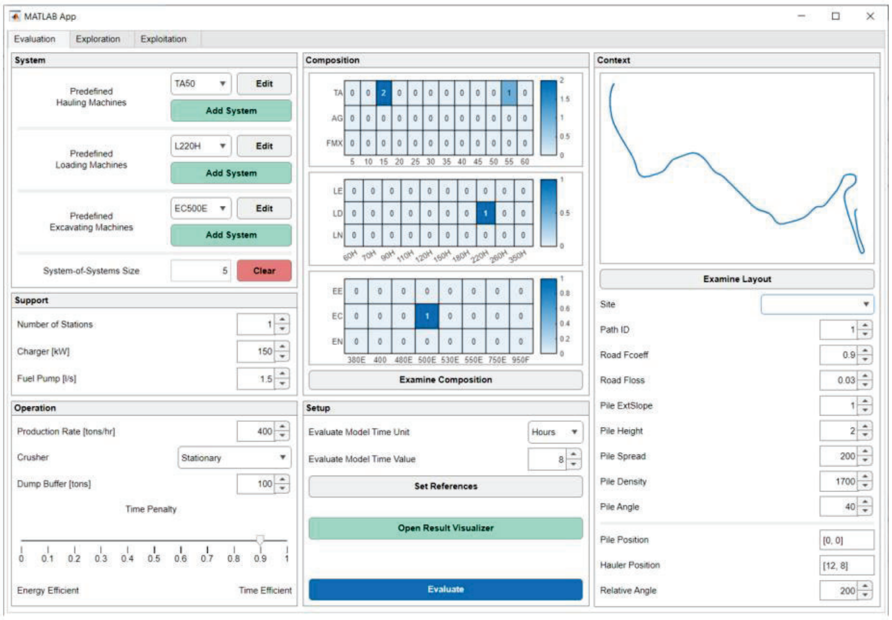


Figure 22: Evaluate Tab in the Application

Figure 23: Explore Tab in the Application

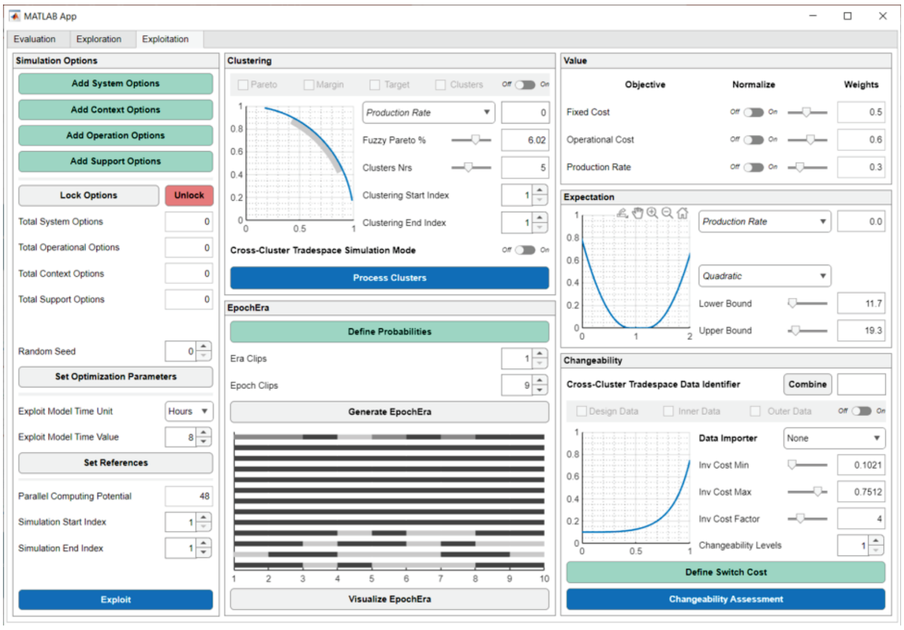


Figure 24: Exploit Tab in the Application

Site demonstration

Throughout the project, two main quarries have been used as reference. Site A and Site B. Site A has been predominantly used for modelling purposes, while Site B has been used for validation purposes. Both sites have been used for demonstration purposes throughout the project based on the topics to be discussed and addressed during those meetings. The hauling paths of the two sites, along with their elevation profiles, have been illustrated in Figure 25. As shown, the two different sites deviate in both length, elevation, and curvature. Site A is a longer haul, while Site B features a compact quarry.

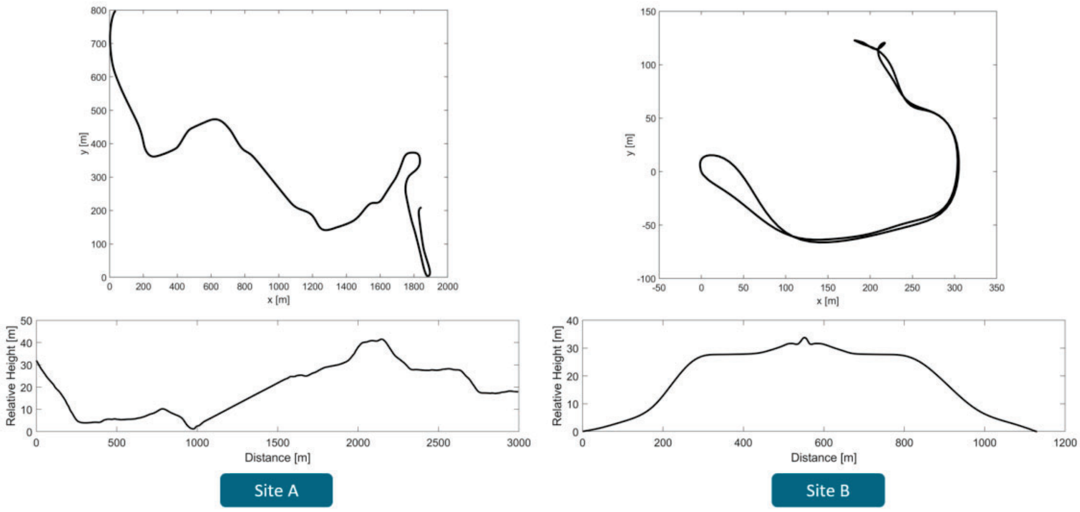


Figure 25: Hauling paths for Site A and Site B, respectively.

Site B was further examined in a field visit and operational data collection. The collected data were analysed to extract valuable operational insights, as illustrated in Figure 26. The bar chart shows time samples of different work tasks as well as the complete cycle time (CT). This data forms a baseline for the calibration of the machine models as well as a starting point for optimisation strategy.

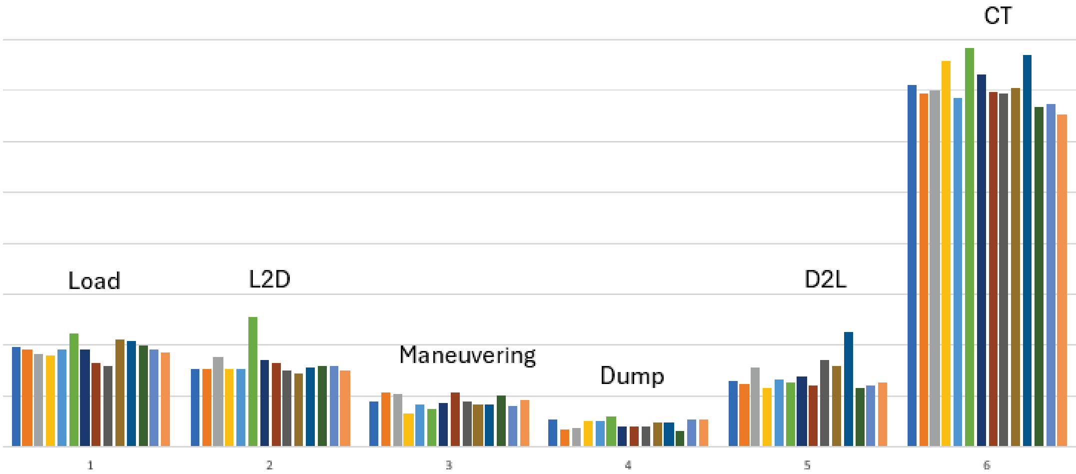


Figure 26: Statistical analysis of the operational data.

As stated, the machine models were calibrated and then used to calculate the optimal velocity profile for Site B. Specifically, a comparison can be made between the collected operational data and the simulated optimal data. Figure 27 shows the velocity profile for a truck from the operational data using the calibrated machine model for a sample work task. This trajectory involves going from the loading point to the dumping point with the applicable payload. The fuel consumption and the gear selection are visualized using the developed models for comparison. Note that absolute values of velocities and gear selected are shown in Figure 27.

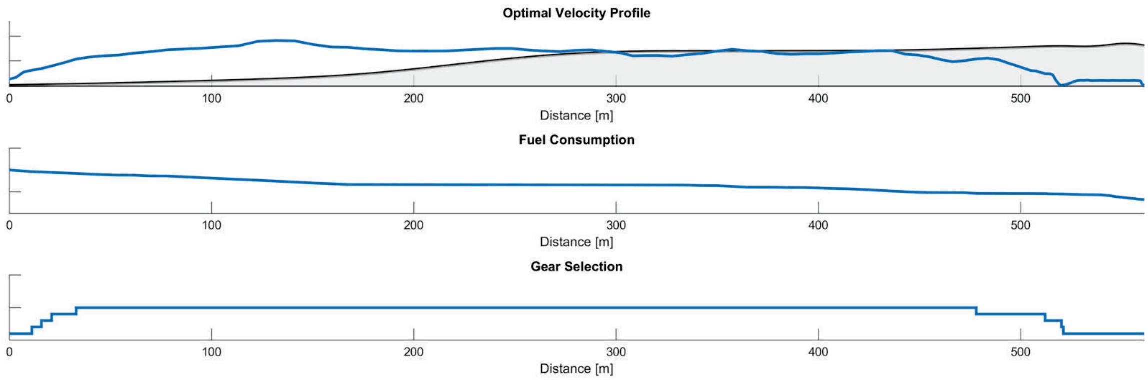


Figure 27: Velocity profile of a truck from the operational data

Figure 28 shows a comparison between the operational velocity (marked by a dashed line) and optimal velocity (marked by a solid line) for the hauler. The optimal velocity was calculated using a relatively higher penalization on time, and thus, these profiles are time efficient. Also, the fuel consumption and the gear selection are visualized using the developed models. Again, absolute values of velocities and gear selected are shown. The difference between the operational and optimal velocity profiles arises from the exploitation of limitations within the model, such as friction limits, lateral stability constraints, and rollover thresholds, i.e., the control policy pushes the machine model to the limits at every single instance.

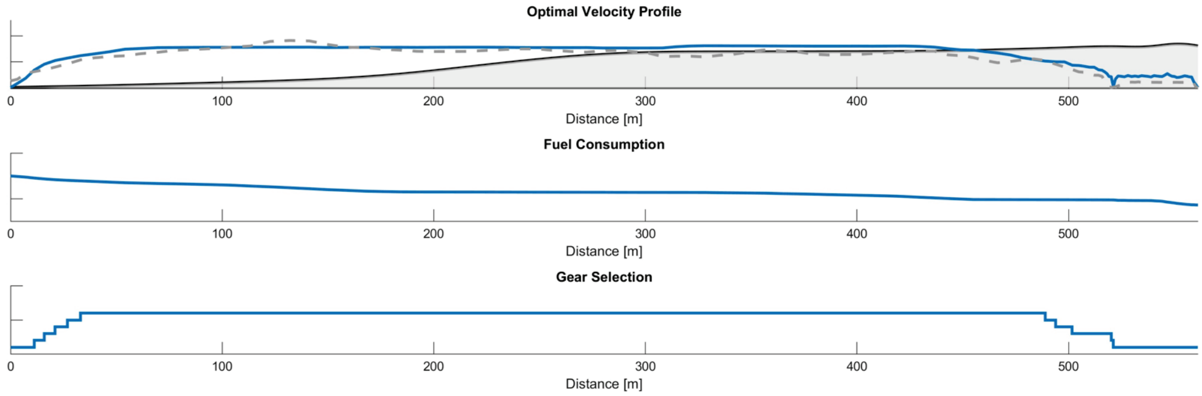


Figure 28: Optimal velocity profile of a truck using simulation models

A similar analysis can be done for loading machines. Since the trajectory is not fixed for the wheel loaders, a comparison between the operational and the optimal trajectory is shown in Figure 29. The operational trajectory is a typical trajectory extracted from the dataset. As mentioned previously, the optimal trajectory was found using an algorithm to minimize the distance in 2D space. In comparison, the optimal trajectory had about a 5% reduction in travel distance.

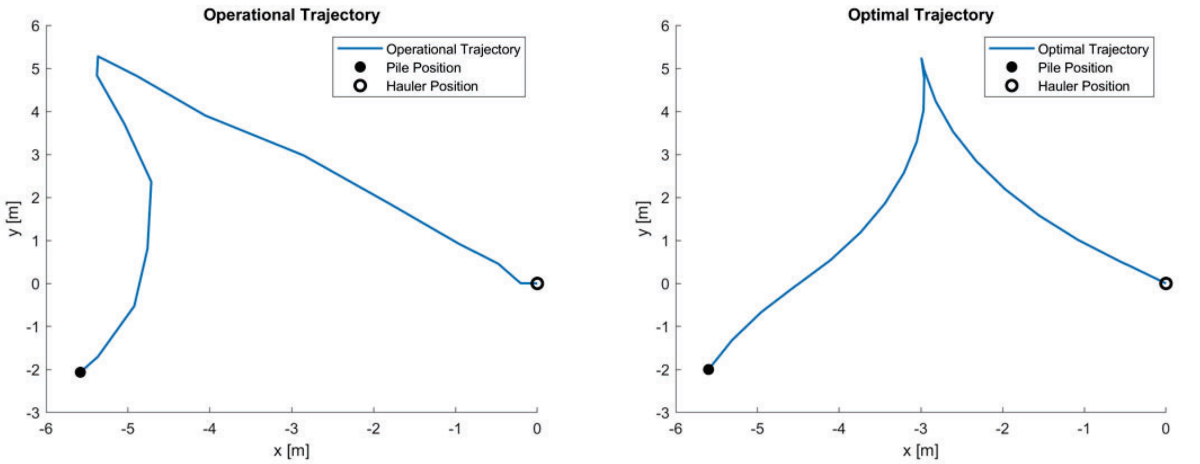


Figure 29: Comparison between the operational and the optimal trajectory for the wheel loader

Figure 30 shows a comparison between the operational velocity (marked by a dashed line) and optimal velocity (marked by a solid line). Again, the optimal velocity was calculated using a relatively higher penalization on time. Some of the machine's other relevant states have also been plotted. The states are discretized in spatial space since different velocities would lead to different times for completing the task. As a result, the loading subtask shows a discontinuity in its state variables. This abrupt change stems from the machine's relatively prolonged interaction with the material pile during penetration compared to the distance travelled in the form of penetration.

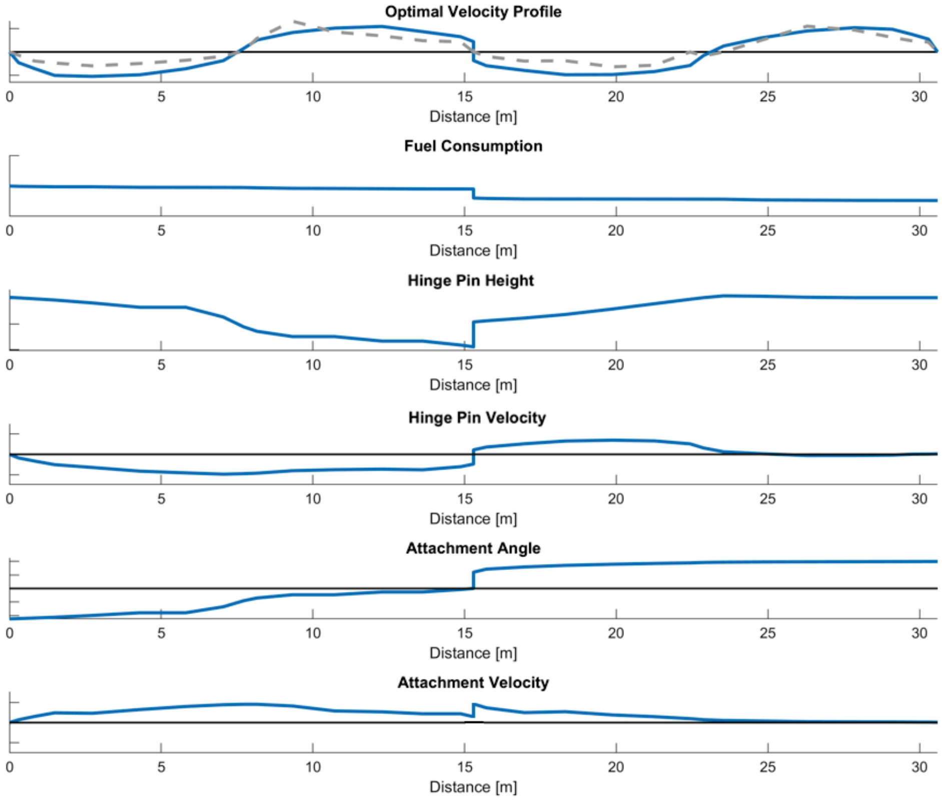


Figure 30: Comparison between the operational and optimal velocity profile for the wheel loader.

Both the truck model and wheel loader model indicate room for improvement. However, the actual gains on a site level might differ when looking at energy consumption, cost per ton, and utilization aspects, which are all essential KPIs for a quarry. To assess this, a site simulation was conducted using both the current operational behaviour at the machine level (based on collected operational data) and optimized behaviour for either eco-efficiency or speed. Additionally, the current fleet was also compared to an electric fleet using the TA15 autonomous-electric hauler. The site simulation results, or these total five operational scenarios are illustrated in Figure 31 and denoted in Table 6. All scenarios are compared using the energy consumption, cost per ton, and utilization normalized with the current state as a baseline. The results show that site B has room for improvement, especially if an eco-efficient driving strategy is adopted. Moreover, both electric fleet renders lower cost per ton despite, in the case of 4 x TA15, having significantly higher energy consumption. This is due to the relative cheapness of electricity compared to diesel.

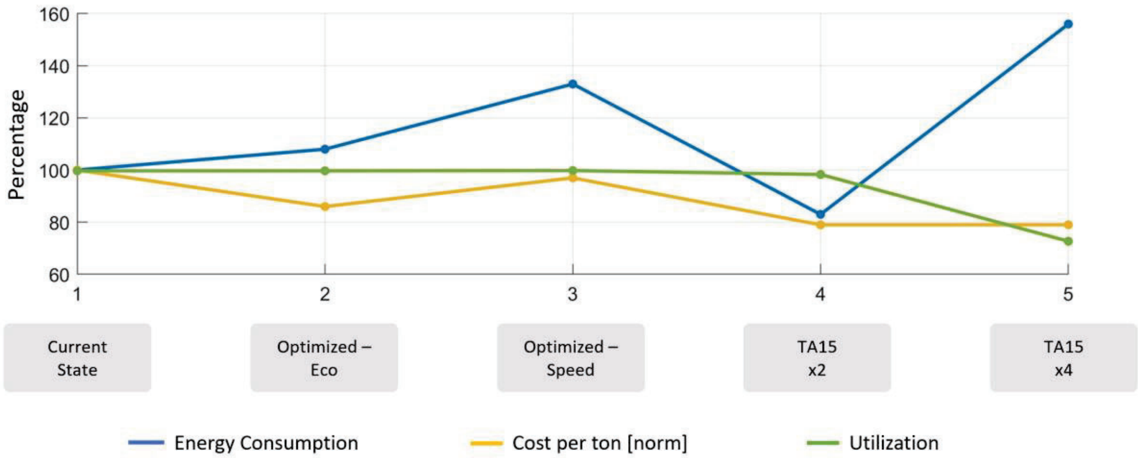


Figure 31: Site simulation result comparison for five different operational scenarios.

Table 6: Result table for five different operational scenarios.

	Real world	Optimized - Eco	Optimized - Speed	TA15 x 2	TA15 x 4
Energy consumption	100%	108%	133%	83%	156%
Cost per ton [norm]	100%	86%	97%	79%	79%
Utilization	99,7%	99,7%	99,8%	98,3%	72,7%

For site A, the site model was used to run multiple operational scenarios and produce KPIs that were later analysed to identify opportunities for optimizing overall site performance. At the site level, the site model was employed to simulate multiple operational scenarios, enabling the evaluation of various workflows and their impact on overall site performance. These simulations produced a comprehensive set of Key Performance Indicators (KPIs), including metrics such as productivity, energy consumption, resource utilization, and environmental impact. The generated KPIs were then analyzed to identify bottlenecks, inefficiencies, and potential opportunities for optimizing site operations. For example, Figure 32 illustrates the execution of one scenario for Site A, highlighting the specific tasks performed by each machine and their contribution to overall site operations. This detailed visualization not only aids in refining current workflows but also serves as a valuable tool for strategic planning and driving long-term performance enhancements.

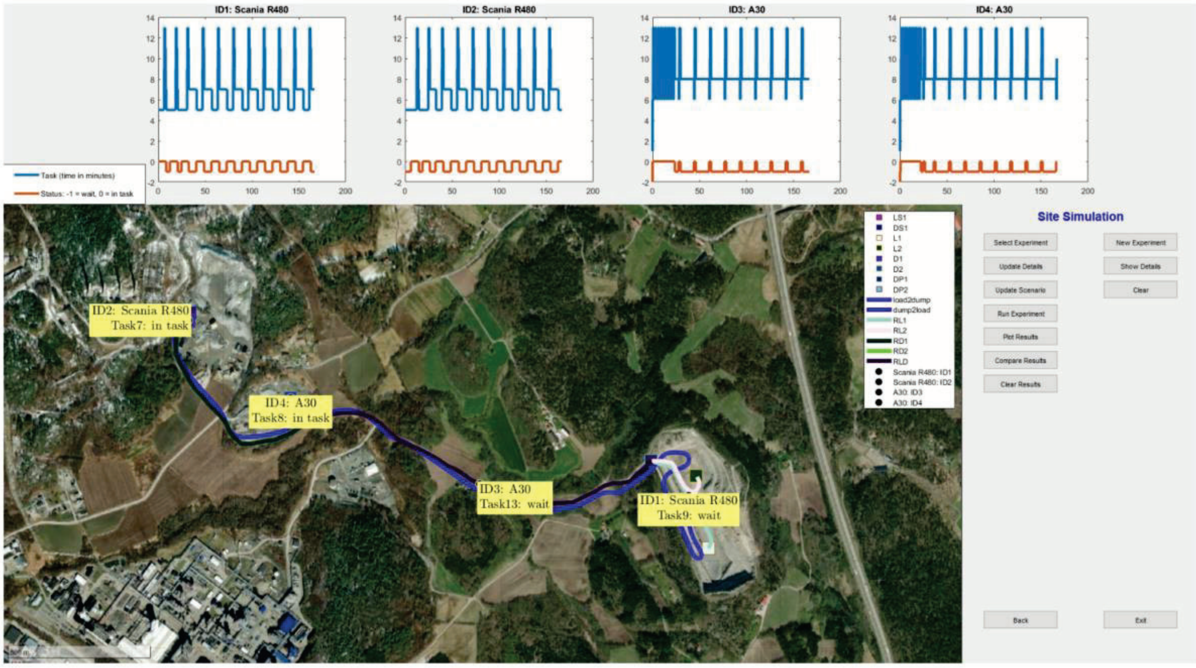


Figure 32: Exemplary snip of simulation execution for Site A

5.2 Contribution to FFI goals (program and sub-program)

5.2.1 Contribution to FFI program goals

The TRUST-SOS project contributed to the Vinnova FFI program by addressing the inefficiencies in off-road site and fleet operations, which currently rely heavily on experience-based decision-making. These decisions are typically made by a few skilled individuals, leading to suboptimal resource utilization and difficulty in managing complex trade-offs across the value chain. TRUST-SOS had to overcome these challenges by developing a reliable and trusted decision support system, utilizing site modelling, machine and site simulation, and optimisation techniques across all levels. By transitioning from experience-based to model-based decision processes, the project introduced digitalized services for off-road transport applications, enabling simulation, optimisation, and advanced data analytics. This shift not only enhanced operational efficiency but also contributed to sustainability goals by optimizing equipment usage, equipment selection, and reducing inefficiencies, thus aligning with the FFI program's emphasis on innovation, sustainability, and increased automation in off-road transport applications.

5.2.1 Contribution to FFI sub-program goals

The TRUST-SOS project contributed to the FFI sub-program goals of promoting fossil-free work machines by advancing digitalized services that optimized energy efficiency, resource utilization, and environmental impact in off-road transport applications. By developing a model-based decision-making support system, the project helped transition from experience-based to data-driven, digital service-based operations, aligning with efforts to reduce climate emissions and enhance Swedish competitiveness in the work machine sector. The decision support system accounted for key factors such as operator skill, asset performance, and site conditions, enabling simulation and optimisation of site operations to improve productivity and efficiency while minimizing environmental impact. Additionally, the project's vehicle and mobility models were modular and adaptable, allowing for real-time monitoring and optimisation of machine performance, fleet configuration, and construction site layout. These models directly contributed to system efficiency and supported the transition to fossil-free operations by exploring the use of electrical machines. The KPI and value-centric approach allowed for vastly different fleet concepts to be objectively compared and created a unified metric capturing the entire value chain. This supports the electromobility transition by allowing electric and diesel machines to be compared more easily and from a lifecycle perspective. The project also supported automation and decision-making processes that enabled smoother transitions to electrical operation, further aligning with the FFI sub-program's goal to foster the development and market introduction of fossil-free work machines.

6 Dissemination and Publication

6.1 Dissemination of knowledge and results

Knowledge and results were disseminated through several channels. This includes public presentations, lectures, demonstrators, workshops, conferences, and social media outreach. This ensured broad visibility and engagement across various stakeholders. Table 7 further elaborates on the knowledge and dissemination of results.

Table 7: Knowledge and dissemination of results.

How have/will the project results be used and disseminated?	Mark with x	Comment

Increase the knowledge within the area	x	- Site modelling and optimizing using discrete event simulation (DES) and agent-based simulation (ABS).
		  - Dump truck/electric truck modelling and optimizing transportation tasks
		  - Wheel loader modelling and optimizing transportation and loading tasks.
		  - Integrating models into one platform and presenting the KPIs on a dashboard.
		- Digital servitisation.
		- Presentations to industry partners, NCC in this case, that are now part of the continuation project.
		- Dissemination at conferences and through publications.

Carried over to other advanced technical development projects	x	Tested-SOS project: Vinnova FFI in transport and mobility services
Carried over to product development projects	x	During this research project the industrial part have built confidence and competence to move into the area of services around fleet- and site optimisation at a deeper level than before, e.g. “Site optimisation” that will be launched during spring, much due to the knowledge build in projects like this.
Introduced to the market	x	Branch-off according to above.
Used in investigations/regulations/ permit matters/political decisions		

PhD and licentiate dissertations

- Philip Wickberg will defend his licentiate in multi-layer dynamic maps in March 2025.
- Abdulkarim Habbab will defend his licentiate in Physics-Informed Machine Learning for Modelling and Control of heavy-duty machinery in June 2025.

Events and talks

- Poster Volvo research days 2021, 2022, 2023.
- Poster IndTech research days 2021, 2022, 2023.

- Presenting papers at conferences and workshops.
- International Conference in Engineering Design (ICED) 2023, Bordeaux, France
- Design conference 2024, Cavat, Croatia

6.2 Publications

6.2.1 Journal articles (3)

1. **Moving from servitization to digital servitization: Identifying the required dynamic capabilities and related microfoundations to facilitate the transition** (Feb 2023), Koteshwar Chirumalla, Luna Leoni , Pejvak Oghazi, Journal of Business Research (JBR) https://doi.org/10.1016/j.jbusres.2023.113668
2. **Remote integration of advanced manufacturing technologies into production systems: integration processes, key challenges and mitigation actions** (Jan 2023), Anas Fattouh, Koteshwar Chirumalla, Mats Ahlskog, Moris Behnam, Leo Hatvani, Jessica Bruch, Journal of Manufacturing Technology Management (JMTM) https://doi.org/10.1108/JMTM-02-2022-0087
3. **Incorporating changeability for value-robust product-service systems: an integrative review** (2024) Machchhar, R.J., Bertoni, A., Wall, J., Larsson, T., 2024. Design Science 10, e8. https://doi.org/10.1017/dsj.2024.5

6.2.2 Conference/Workshop Paper (12)

1. **Exploring Dynamic Map Validation at Construction Sites: A Case Study and Feasibility Analysis,** Philip Wickberg, Anas Fattouh, Sara Afshar, Markus Bohlin, 27th IEEE International Conference on Intelligent Transportation Systems (ITSC 2024)
2. **A Multilevel Modelling Framework for Quarry Site Operations (Apr 2024),** Abdulkarim Habbab, Anas Fattouh, Bobbie Frank , Elianne Lindmark , Koteshwar Chirumalla, Markus Bohlin, 12th ACM/IEEE International Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems (SESoS 2024) https://doi.org/10.1145/3643655.3643881
3. **Digital micro-services on an AI-based construction site simulation platform: Exploring service types and key challenges (Nov 2023),** Ignat Kulkov, Koteshwar Chirumalla, Anas Fattouh, 10th International Conference on Business Servitization (ICBS 2023) https://www.ipr.mdu.se/pdf_publications/6768.pdf
4. **Adopting a Digital Twin Framework for Autonomous Machine Operation at Construction Sites (Oct 2023),** Philip Wickberg, Anas Fattouh, Sara Afshar, Markus Bohlin, The 7th CAA International Conference on Vehicular Control and Intelligence (CVCI 2023) https://doi.org/10.1109/CVCI59596.2023.10397254
5. **Mapping simulation optimization requirements for construction sites: A study in the heavy-duty vehicles industry (Oct 2023),** Abdulkarim Habbab, Anas Fattouh, Bobbie Frank , Koteshwar Chirumalla, Markus Bohlin, 64th International Conference of Scandinavian Simulation Society (SIMS 2023) https://doi.org/10.3384/ecp200047
6. **Dynamic Maps Requirements for Autonomous Navigation on Construction Sites (Dec 2022)** Philip Wickberg, Anas Fattouh, Sara Afshar, Johan Sjöberg , Markus Bohlin, The 5th International Conference on Communications, Signal Processing, and their Applications (ICCSPA'22) https://doi.org/10.1109/ICCSPA55860.2022.10019082
7. **An Integrated Simulation Framework for Construction Site Operations (Dec 2022),** Anas Fattouh, 1st IEEE Industrial Electronics Society Annual On-Line Conference (ONCON2022) https://doi.org/10.1109/oncon56984.2022.10126772
8. **Merging agent-based simulation and vehicle dynamics: a hybrid approach for value exploration in the mining industry (May 2024)** Toller Melén, C.N.K.T., Machchhar, R.J., Bertoni, A., 2024., in: Proceedings of the Design Society. pp. 2755–2764. https://doi.org/10.1017/pds.2024.278
9. **A tradespace exploration approach for changeability assessment from a system-of-systems perspective: application from the construction machinery industry (May 2024)** Machchhar, R.J., Toller Melén, C.N.K.T., Bertoni, A., 2024., in: Proceedings of the Design Society. pp. 2655–2664. https://doi.org/10.1017/pds.2024.268

10. **Towards Digital Immersive Experiences for Collaborative Value Co-creation in Design (September 2023)** Bertoni, M., 2023., in: Camarinha-Matos, L.M., Boucher, X., Ortiz, A. (Eds.), Collaborative Networks in Digitalization and Society 5.0. Springer Nature Switzerland, Cham, pp. 193–206. https://doi.org/10.1007/978-3-031-42622-3_14
11. **Leveraging Information Visualization Through Extended Reality (XR) for Incorporating Changeability in Product-Service Systems (September 2023)** Machchhar, R.J., Scurati, G.W., Bertoni, A., 2023., in: Camarinha-Matos, L.M., Boucher, X., Ortiz, A. (Eds.), Collaborative Networks in Digitalization and Society 5.0, IFIP Advances in Information and Communication Technology. Springer Nature Switzerland, Cham, pp. 255–268. https://doi.org/10.1007/978-3-031-42622-3_18
12. **Supporting changeability quantification in product-service systems via clustering algorithm (August 2023)** Machchhar, R.J., Aeddula, O.K., Bertoni, A., Wall, J., Larsson, T., 2023., in: Proceedings of the Design Society. Cambridge University Press, pp. 3225–3234. https://doi.org/10.1017/pds.2023.323

6.2.3 Work in Progress (7)

1. **Efficient Torque Prediction in Wheel Loader Engines: Integrating Feature Selection, Machine Learning, and SHAP with Operational Context (2025)**, Abdulkarim Habbab, Anas Fattouh, Mohammad Loni, Koteshwar Chirumalla, Markus Bohlin, Bobbie Frank, International Journal of Data Science and Analytics (submitted)
2. **Software-Defined DES (Patent Application),** Anas Fattouh, Bobbie Frank
3. **Operational and Environmental Optimization through Digital Platforms in Off-Road Site Management,** Ignat Kulkov, Koteshwar Chirumalla, Anas Fattouh
4. **Designing value robust circular systems through changeability: a framework with case studies,** Bertoni, A, Machchhar, R.J., Toller Melén, C.N.K, Scurati, G.W., Bertoni, M. (submitted to journal)
5. **Effective System-of-Systems simulation in a VUCA world: lessons learned for design decision-makers,** Toller Melén, C, Bertoni, M, Johansson Askling, C (submitted to conference)
6. **Combining Dynamic Programming and Reinforcement Learning to facilitate Tradespace Exploration in Changeability Assessment,** Machchhar, R.J., Bertoni, A., 2025. (submitted to conference)
7. **A framework for context-based System-of-Systems value exploration,** Toller Melén, C, Machchhar, M, Wendin, C, Bertoni, M, (Submitted to journal)

7 Conclusions and Continued Research

The task at hand of this project, to do entire site, fleet, and machine optimization, was steeper than initially anticipated. However, great progress has been achieved during the project, adding a lot of knowledge and insight for industry, end users, and academia alike. Hence, a continuation project has already been started. This project has further provided a base architecture that will support future research projects and expansion. As a result, the ambition is that this project can serve as leverage and enable more rapid development in future projects, ultimately providing a basis for the so-called ketchup-effect.

The TRUST-SOS project successfully addressed key challenges in off-road transport applications by developing a model-based decision support system that optimized site operations, improved resource utilization, and reduced environmental impact. By moving from experience-based to data-driven decision-making, the project enabled simulation and optimisation of complex quarry site environments, enhancing productivity and efficiency while supporting sustainability goals. The development of modular vehicle and mobility models allowed for monitoring and optimisation of machine performance, fleet configuration, while considering site layout, contributing to the overall system efficiency and reducing reliance on fossil fuels. Additionally, the project fostered the transition toward electrification through advanced automation and optimisation techniques as well as the development of KPI and value metrics for site performance, aligning with the broader objectives of the FFI sub-program to support the development of fossil-free work machines.

While the TRUST-SOS project made significant advances in optimizing off-road transport operations, several areas offer potential for further research and development. Future work could focus on:

- Advanced Machine Learning Techniques: The application of deep learning and reinforcement learning models to enhance the predictive capabilities of the decision support system, allowing for more adaptive and autonomous operations in dynamic environments.
- Electrification: Continued development of models of electric machines, focusing on battery management, charging infrastructure, and energy optimisation in off-road applications.
- Automation and Autonomous Operations: Expanding automation capabilities to fully autonomous off-road transport systems that can manage complex quarry operations with minimal human intervention, reducing both operational costs and environmental impact. This includes expanding the capabilities of work tasks possible in autonomy mode.
- Circular Economy and Resource Efficiency: Exploring opportunities for circular economy principles, such as reusing materials and optimizing the life cycle of equipment, to improve resource efficiency and reduce waste in quarry operations.
- Digital Servitisation: Exploring the integration of data-driven services into a comprehensive digital platform to facilitate new revenue streams and enhance customer relationships, supporting the transition toward more sustainable and efficient work environments.
- Expanding simulation scope: Further enhance site design and optimisation by including stockpile location and size. Also adding stationary equipment such as crushers and screeners, all based on customer demands.

8 Participating Parties and Contact Persons

The project has included representatives from Mälardalen University, Blekinge Institute of Technology and Volvo Construction Equipment. To perform site mapping and provide data on site operations, NCC AB was used as an external partner for the project.

- **Volvo Construction Equipment (Volvo CE)**
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