# Future Electrified Mobile Machines "FEMMa"

FEMMa

Public Content Report (published in December 2024)

# Contents

# 1 Preface

Most value chains in the modern society and economy contain operation of heavy working machines (WM); good examples are mining and construction, agriculture, forestry, and material handling logistics. Finland has a world-leading position in providing technology for WM operations in these areas. However, maintaining this position is challenging while both climate related drivers and the rapid development in key enabling innovations are assumed to disrupt technology, value chains and business models.

EU, nations, cities, and individual companies have set ambitious targets to be climate neutral in the near future (EU 2050, Finland 2035). For WM industry an apparent approach is to make transition from conventional fossil fuels to electric power sources. The transition is a major challenge for WM industry but diligently executed can provide a huge competitive advantage.

The rapid digital technology development means more powerful computing systems, faster communication, larger storage capacity, new sensors, new algorithms, etc. The digital technologies launched a transition from current paper-based or analogue technologies and work procedures to digital ones, but moreover, the digital technologies will also transform entire value chains and value creation mechanisms to new, currently unknown ones.

WM industry has utilized recent digital technology development for creating automatic functions and autonomous features, integrating WMs to back-end systems, and providing interface to the value chain. However, fast technology development provides a great opportunity to revolutionize work procedures and value creation mechanisms in mines, farms, forests, harbours, and other areas where WM are used.

Finnish companies are aware of the above-mentioned development and are prepared for the challenge. The companies have recognized a high need for new science-based research to create adequate competencies for the future.

The leading Finnish companies in mobile machinery, Sandvik, Ponsse, Cargotec, and Ioncor (Valmet Automotive), have created a technology roadmap with the aim of guiding cutting-edge research on world-class mobile machinery. FEMMa project is a joint effort of Tampere University (TAU) and Technical Research Centre of Finland Ltd (VTT) supported by the leading companies. The consortium is highly cross-disciplinary and represents scientific expertise from a wide variety of topics such as power systems, power electronics, battery systems, software engineering, electrified vehicles, mobile machines, automation, and business model innovations. This research, together with SIX Mobile Work Machines ecosystem is the launch of multidisciplinary collaboration and ecosystem to enhance the development of electrified working machines. This research forms the first important steps in electrification of the working machines, and the focus is on the technologies and methods that are fundamental for replacing fossil-fuel-based power sources, enabling the improvement in productivity and extending the life-cycle of the working machines; all important drivers for sustainability.

The grand challenge for the whole industry of the mobile working machines is How to make the customers' operations carbon free? The main assumption is that carbon free operations are possible by electrifying the work machines. At the same time, gains in efficiency, productivity and economy can be reached. Transition to carbon free operations is driven by regulations but can be accelerated if the new electrified working machines are more durable, simpler, lighter, more efficient, and more economic to operate. Electrification enables simpler construction and together with digitalisation enables efficiency.

This general research question related to the system-of-systems can be scrutinised in four separate perspectives. The perspectives are:

- How energy usage, power usage, work cycle, and thermal issues must be considered in an electrified mobile work machine and its core components, and how the electric power shall be distributed in a worksite?
- How electrification of a mobile work machine affects autonomous operations and how the digitalisation enables autonomous operation within the continuously changing worksite context?

- What digital solutions are needed to autonomy and electrification such that true autonomous distributed operation is enabled and simultaneously data collected by WMs can be utilised?
- What added value the electrified and digital solutions provide and how digital technologies facilitate business model innovation?

These general perspectives and the related research questions are further elaborated in this final report of FEMMa project.

Prof. Matti Vilkko, Scientific Director

Tampere University

Kalle Einola, Chairman of the Steering Committee

Ponsse Oyj

# 2 FEMMa project in brief

## 2.1 FEMMa in numbers

Duration: 1.9.2021 – 1.8.2024

Budget: 3 M€

## 2.2 Consortium

TAU, VTT

## 2.3 Industry partners

Kalmar, Ponsse, Sandvik, Ioncor (Valmet Automotive)

## 2.4 Funding

Business Finland, Industry partners, TAU, VTT

# 3 International collaboration and networking

Alexander Schock-Schmidtke, from Technical University of Munich - Chair of Materials Handling, Material Flow, and Logistics, visited TAU on 13.05.2024 - 16.08.2024. International exchange in the field of construction machinery automation. The Technical University of Munich develops autonomous construction machinery and robots for the construction site. As part of the research exchange, joint research is to be carried out into software solutions for environment recognition in the off-highway sector. The research visit focussed on the development of a software framework for the creation of dynamic occupancy grid maps with radar sensor data. The framework is to be used for autonomous construction machinery.

Minh Tran, Tampere University, visited Aalborg University 1.3.2023 - 27.8.2023. The aim of researcher mobility was to develop methods for the aging examination of batteries and to carry out such examinations with these methods. In addition, the aim was to validate analysis tools based on battery impedance measurements previously developed during the project. The objectives were achieved and the methods developed were extensively utilised after researcher mobility at a later stage of the project. Research mobility also produced scientific co-operation publications and provided the basis for long-term co-operation, which continues today.

Luca Romagnuolo from University of Sannio, Benevento, visited Tampere University 02.01.2024 – 30.03.2024. The work focused on performing co-simulation in Matlab/simulink and Amesim, design a cooling system for sWille thermal study. The goal was in getting expertise to the group related to cavitation and pump failure. Building collaboration with Universityu of Sannio, Italy. Plan is to have 1 conference piblication and journal paper.

Majid Najafpour Ahangar from Iran University of Science and Technology 1.12.2023 - 30.4.2024. The aim of researcher mobility was to develop methods for controlling the temperature of batteries and to do modeling related to the thermal behaviour of batteries. The benefits of researcher mobility for the project were significant; the results achieved strengthened the dynamic modelling methods developed for batteries during the project. Research mobility also contributed to the completion of Task 1.2 in particular. Research mobility also produced collaborative articles, as well as capabilities for future collaboration.

Majid Najafpour Ahangar from Iran University of Science and Technology visited Tampere University 27.11.2023 - 31.8.2024. His research focusede on real-time temperature prediction in battery systems. The mobility aims to enhance battery modeling through: 1) Low-temperature behavior analysis using high pulse power charactization and computational fluid dynamic simulations. 2) Reduced order model and Digital Twin development, validated via experimental tests. Benefits include: 1) Improved research accuracy in battery technology. 2) Innovative thermal management strategies. 3) Strengthened international collaboration and knowledge exchange. 4) Laying groundwork for electrified machine innovations.

Doniyor Urishov at VTT visited SINTEF in Norway. The primary goal of the visit to SINTEF was to gain comprehensive understanding of physics-based modelling for batteries, specifically utilizing the BattMo toolbox. This visit was strategically aimed at enhancing the expertise and proficiency in the application of this advanced modelling tool for battery technology. Key activities included receiving training on the usage of the open-source battery modelling tool BattMo, developed by SINTEF, along with learning about parameter extraction methodologies and experimental methods in this field.

Marko Antila at VTT has participated actively to CharIN (Charging Interface Initiative) international Focus Groups and Task Forces for Megawatt Charging Systems (MCS). This pre-normative work has produced several white papers, including the paper for ruggedized MCS, which is especially suitable for NRMM usage. Furthermore, VTT has participated to IEC TC69 standardisation working group, especially for the MCS charging delta standard IEC 61851-23-3, and voted for the technical solutions which support Finnish and European NRMM industry.

# 4 Company statements – Benefits for participants

## 4.1 IONCOR

IONCOR Oy is a manufacturer of battery systems for electric vehicles. The Company has over 50 years of experience in the automotive industry and is one of Europe's leading suppliers of battery systems. Ioncor's modular battery products enable the electrification of a wide range of applications, such as agriculture, forestry, material handling, buses, and trucks.

By participating in the Femma project, we gained a unique opportunity to network and collaborate with other industrial companies and academia. We were able to share our own expertise and at the same time learn. In addition, we gained access to valuable research results that helped us to develop our own operations.

Best regards,

**Ville Nousiainen**

Specialist, Fund management, CF Program Management

Mobile: +358400416267

E-mail: ville.nousiainen@ioncor-batteries.com

## 4.2 PONSSE

PONSSE Plc plays a crucial role in advancing sustainable cut-to-length forestry through its innovative technologies, productive and efficient machine designs, and commitment to responsible forest management practices. As a leading manufacturer of CTL forestry machinery since 1970, new technologies such as the electrification of powertrains and autonomous solutions are both seen as key enablers for a more sustainable future in the industry.

By joining the FEMMa Co-research project, we had an excellent opportunity to understand and define the enabling technologies of the future. This was done with strong research partners, as well as a solid industrial consortium whose needs were very well aligned. As project outcomes, a lot of new knowledge was accumulated in the field of future mobile work machines and their key enabling technologies – both in academia and in the companies.

Ponsse Plc

Kalle Einola

Director

Research & Programs

# 5 Theme 1: Power and thermal management of an electrified NRMM

## 5.1 Summary

The power and thermal management of electrified NRMM was divided into 4 subthemes.

- System modelling for thermal management
- Real-time impedance measurements of batteries
- Li-ion battery lifetime evaluation
- Dimensioning of batteries and charging

## 5.2 System modeling for thermal management

### 5.2.1 Problem/challange/need description

Generators and actuators are usually designed for so-called "rated load" conditions, which means a continuous or periodic loading that causes the maximum allowed temperature rise. In working machines (WM), periodic loadings seldom exist, and each individual component may experience a different stochastic loading profile. Thus, the traditional design approaches easily lead to overly heavy and expensive systems. A system-level modelling approach facilitates shifting from individual component selection to a new system-level design methodology, which is expected to lead to weight and cost reductions. For such an approach, computationally efficient power loss and thermal models covering the whole WM drive-train system need to be developed. Such tools allow redesigning and optimizing the cooling systems, for example, by combining the individual cooling cycles of hydraulic and electric actuators into one common cycle.

In the beginning of the project, the following questions were formed based on the industrial needs:

a) What are the most suitable models for realistically describing the heat dissipation of all active components in an electro-hydraulic WM (e.g., battery, diesel engine, generator, power electronics, electric motors, hydraulic actuators) under different loadings and operating temperatures?

b) What kind of model order reduction techniques can be used to compress the information in the aforementioned models to produce computationally efficient tools for long time-domain simulations?

c) How to sufficiently couple the reduced models of the individual components to create a tool for simulating the heat production and transfer in the whole electro-hydraulic drive system under stochastic loading profiles?

d) Being able to accurately simulate the thermal behaviour over realistic loading profiles, how to control and distribute the power flow to individual components in such a way that the overall heat dissipation in the system is minimized?

e) By utilizing the new simulation and control methodologies in design of WMs, what kind of weight and cost reductions can we achieve in different applications by decreasing the design safety margins and thus the power rating and size of individual components and the cooling arrangements?

### 5.2.2 Approach and solution

The system-level modelling of the WM drive train consists of two parts: 1) modelling of the loss dissipation in the individual components (e.g. electric motor and battery) under different loading conditions and ambient temperatures, and 2) modelling the heat transfer and temperature distribution in the WM using the loss models as heat sources. The primary modelling tools were computational electromagnetic analysis and lumped-parameter electrical and thermal models. Core loss models for synchronous machines were developed based on a numerical magnetic field solution and implemented in a computationally efficient way in a system simulation tool by storing precalculated data in lookup tables. The loss model was validated against existing calorimetric loss measurements and allows roughly a 100-fold speedup compared to a transient finite element model without compromising the accuracy of core loss calculation. A new lookup-table based control algorithm was developed for synchronous machines to minimize total loss dissipation for a given torque (Figure 1). Losses in hydraulic actuators were described by dynamic friction models, while losses in batteries were modelled by semi-empirical lumped-parameter electrical equivalent circuit model accompanied with a model for reversible heat generation, which is associated with the entropy change in the electrodes resulting from structural changes caused by the intercalation of lithium ions during charging and discharging. The developed battery models were validated in controlled laboratory conditions in VTT battery laboratory. Temperature measurements were performed for fine-tuning of the battery model parameters, in particular heat transfer coefficients which are difficult to estimate by other means. Validating the system-level model and the proposed control management system was based on initial experimental loading data (speed, force / torque) with TAU's conventional diesel-hydraulic wheel loader. In addition, a novel measurement setup was constructed to allow full-load testing of electrical motors and generators that will be used in a 70 kW series hybrid sWille wheel loader that is being developed at TAU.

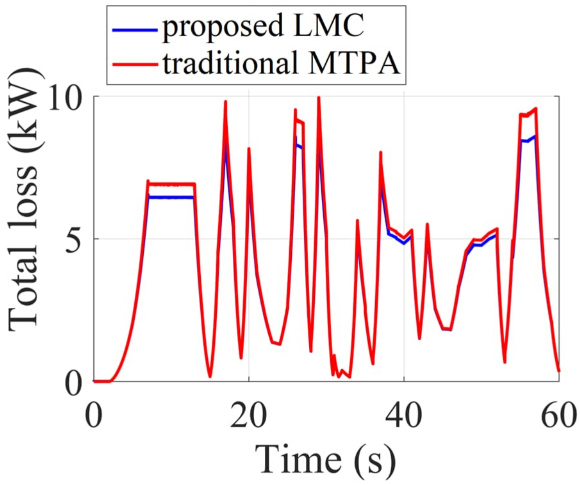



Figure 1 Comparison of the developed loss-minimizing control (LMC) method and a traditional maximum-torque-per-ampere (MTPA) method in a synchronous motor simulation with a real wheel loader duty cycle.

### 5.2.3 Benefits and value

Fast time-domain simulation of the power flows and temperature rise in the design stage of WMs allows to predict the operating temperatures during long-term stochastic loadings. This makes it possible to reduce safety margins in design, which reduces the cost and weight of individual components as well as the cooling arrangements. With the validated simulation models, new powertrain solutions can be investigated by simulating the thermal performance of the whole system under realisitic load cycles and various algorithms for power management, i.e. scheduling the operations of the individual actuators. The individual components can then be re-designed or re-chosen in such a way that their temperatures stay within the specified limits over the studied load cycles. The cooling system of the sWille wheel loader will be designed using the developed methods.

The proposed thermal modeling for batteries and electric motors offers significant benefits and value when applied to off-road machinery. Firstly, it enables optimized system design by assessing heat dissipation characteristics and loss creation. Engineers can strategically position components, and design efficient cooling systems for them. Secondly, efficient cooling and control strategies can be developed based on the proposed loss minimization algorithms. This minimizes energy losses and ensures reliable operation. Thirdly, performance optimization is achievable by fine-tuning system parameters in response to ambient temperature changes. This improves productivity and fuel efficiency through energy savings. Lastly, safety is enhanced by preventing dangerous temperature levels and implementing alarms or shutdown mechanisms. Overall, thermal modeling enhances reliability, efficiency, and safety, making off-road machinery more valuable.

### 5.2.4 Publications


1. C. Dai, H. Khan, A. Abbas, P. Rasilo, T. Minav, "Loss Minimization Control of PMSM for Electrified Non-Road Mobile Machinery Using Flux and Loss Maps", in Proc. ICEM, Torino, Italy, September 2024.
2. M. Ferrari, C. Dai, D. Beltrami, S. Uberti, "Electrification of Non-Road Mobile Machinery: A Tool for Motor Selection", in Proc. ICEM, Torino, Italy, September 2024.
3. O. D. Fernández, A. Hentunen, S. Jenu, M. Allam, A. Gusrialdi, T. Minav, "A Rule-Based Energy Management System Integrating a Semi-Empirical Battery Model for Hybrid Wheel Loaders", Appl. Energy (under review).
4. M. Najafpour, M. Tran, M. H. Shojaeefard, T. Roinila, "Cold-Weather Profiling of Lithium-ion Cell Using Hybrid Pulse Power Characterization", in Proc. ECCE, Phoenix, AZ, USA, October 2024.
5. A. A. Abbas, J. Vesa, H. Khan, H. Chen, Y. Liu, P. Rasilo, "Fast and Accurate Non-linear Model for Synchronous Machines Including Core Losses", IEEE Trans. Energy Convers. (in press).


## 5.3 Real-time impedance measurement in assessing the battery dynamics

### 5.3.1 Problem/challange/need description

The operation of most working machines is often dependent on various li-ion batteries. The number of such batteries will significantly increase in the future as the machines become more electrified. The rapid increase in the number of li-ion batteries in different applications will set several challenges not only in a proper operation of a working machine but also in a circular-economy point of view.

One of the major challenges regarding Li-ion batteries is the battery recycling and usability in second-life applications. Recent studies have shown that approximately 95 percent of Li-ion batteries are landfilled instead of recycled upon reaching end of life. Studies have also shown that almost 95 percent of the battery waste could be recycled not only regarding raw material but also in second-life applications.

Having a technology for reliably evaluating the battery condition and dynamics in working machines can significantly improve the working efficiency as the battery operation can be optimized and unnecessary battery replacements can be avoided. As the battery conditions change over time and with many parameters, methods based on real-time measurements would be most desired.

### 5.3.2 Approach and solution

Li-ion batteries have an integrated battery-management-system (BMS) which applies voltage, current and temperature measurements for computing and monitoring the battery state parameters such as the state-of-charge (SOC) and state-of-health (SOH). The SOC indicates the remaining battery charge (for example, the driving range of an electric vehicle) while the SOH indicates the health of the battery. These parameters are used by the BMS to optimize the battery operation, safety, and efficiency, and therefore, accurate monitoring of the SOC and SOH plays a key role in maximizing the battery lifetime.

While it is difficult to directly measure the battery SOC and SOH, studies have shown that the battery internal impedance can be used to indirectly obtain the SOH and SOC. The impedance is conventionally measured using electrochemical impedance spectroscopy (EIS) in which sinusoidal perturbations are injected on top of the battery nominal output current. The resulting output voltage and current are measured, and Fourier transform is applied to obtain the battery impedance at various frequencies. Although the EIS provides an accurate impedance estimate, the method is limited due to impractical and costly implementation. As a sinusoidal wave carries energy for only one frequency at a time, the EIS-based measurement takes a long measurement time, which would be impractical for measuring a battery with fast-changing dynamical states.

In this project, the conventional EIS-method has been replaced by applying carefully designed pseudo-random binary and near-binary perturbation signals instead of sinusoidal perturbations [5, 10-12]. The applied pseudo-random sequences are broadband signals, which means they have energy at a wide frequency range. The signals have many attractive properties particularly suitable for battery-impedance measurements. The results have shown that applying such sequences the battery impedance can be reliably obtained in a fraction of time compared to the traditional technique (seconds instead of several tens of minutes). As the perturbations have only two or three signal levels, they can be implemented even with a low-cost application the output of which can only cope with a small number of signal levels.

Figure 1 shows a schematic diagram for applying the developed impedance-measurement technique. In the method, the binary or near-binary perturbation is placed, for example, on top of the nominal battery current. The resulting output voltage is measured, and Fourier techniques are applied to extract the information of the battery under test.

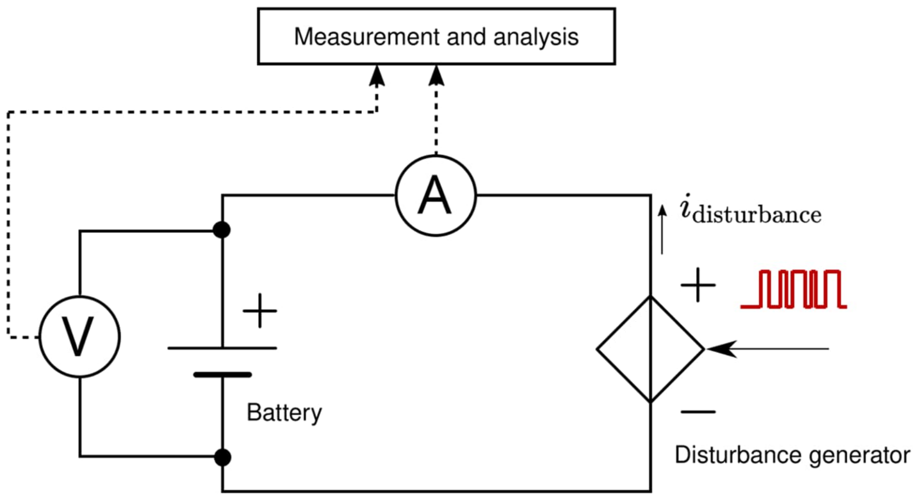



**Figure 1 Battery-impedance measurement setup.**

Figure 1: Battery-impedance measurement setup.

A typical method to represent the obtained results is to use a Nyquist curve as shown in Figure 2. The impedance curve can be divided into several regions that signify various chemical processes in the battery. At low frequencies of less than a few hundred mHz, the electrodes are dominated by diffusion of Li-ions in the crystals. Such processes are represented by a rising line in the Nyquist plot. The mid-frequency region, which usually ranges from several mHz to a few kHz, describes the ion movement between the solid-electrolyte interphase (SEI) layers and the electrodes, known as the charge-transfer (CT) processes. At higher frequencies, inductive behavior starts to dominate and characterizes the overall conduction parts of the battery cell.

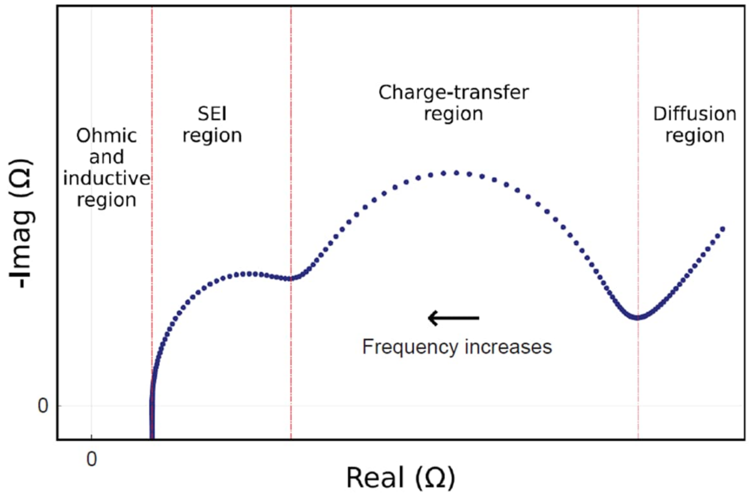



**Figure 2 Battery internal impedance (Nyquist plot).**

Figure 2: Battery internal impedance (Nyquist plot).

Figure 3 shows an example of experimental measurement results. In the experiment, the impedance from 12 differently aged batteries were measured. The batteries were cycled, that is, fully charged and discharged, 0-1000 times. The figure shows how the impedance varies along the battery age.

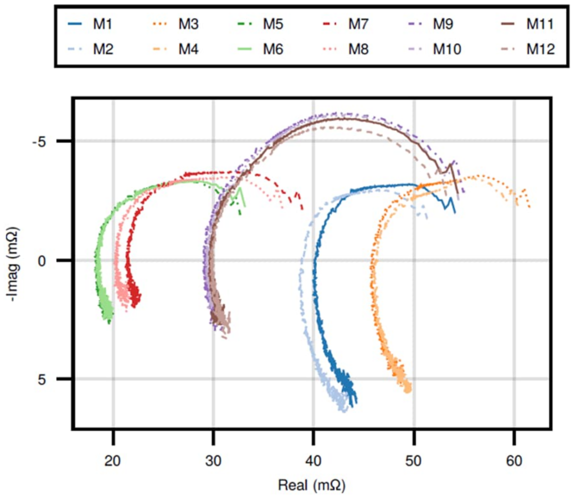



Figure 3: Measured impedance for batteries of different ages.

Figure 4 shows another example of experimental measurements. In the experiment the battery impedance was measured at different temperatures. The figure shows a clear correlation between the measured impedance and temperature. Hence, the developed method potentially provides a convenient approach to make thermal analysis of battery without relying on expensive and complicated temperature sensors.

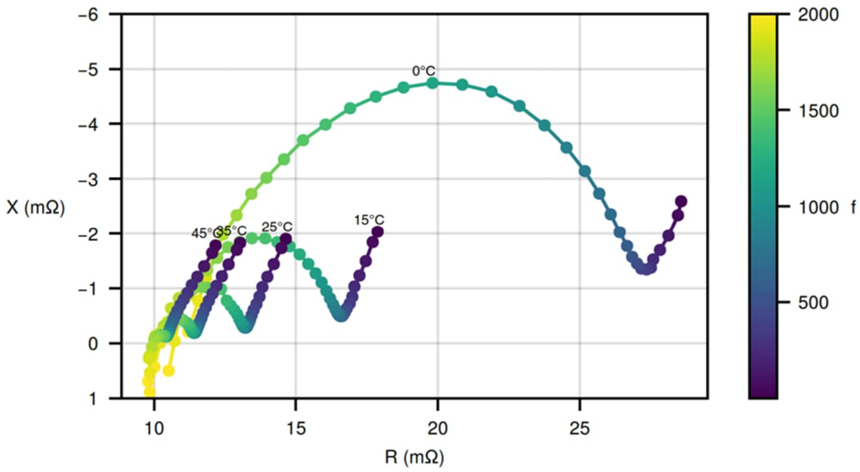



**Figure 3 Measured impedance at various temperatures.**

Figure 4: Measured impedance at various temperatures.

### 5.3.3 Benefits and value

Having accurate information of the battery dynamics provides several benefits. The main benefits can be given as follows.

- Unnecessary and expensive battery replacement can be avoided

Applying the obtained impedance, the battery operation can be optimized, and possible fault sources can be identified. For example, in a large battery pack single cells operating inefficiently can be recognized and replaced.

- Improved battery management leads to improvements in battery safety and lifetime

The obtained impedance can be potentially used to recognize batteries having safety issues. For example, the battery temperature can be monitored in real time through the impedance.

- Improved reusability in second-life applications and recycling possibilities [6]

The results have shown strong correlation between the internal impedance and second-life storage capabilities of Li-ion battery cells. The applied method can be used, for example, to rapidly measure a large number of end-of-life battery cells and to define their applicability for second-life applications.

- Rapid and accurate battery-temperature measurement [7]

Temperature is a critical parameter which heavily influences the safety and performance of Li-ion batteries. The results have shown a strong relationship between the battery impedance and battery temperature. The developed measurement methods can be applied to quickly and accurately measure the battery impedance from which the temperature of a battery cell can be directly estimated without relying on temperature sensors or complicated modeling techniques.

### 5.3.4 Publications

1. M. Tran, L. Lignell, J. Sihvo and T. Roinila, Techniques in Hardware Implementation in Online Li-Ion Battery Cell Impedance Measurements, IEEE Transactions on Industry Applications, 2024 (under review)

2. L. Lignell, M. Tran and T. Roinila, Broadband Methods in Internal-Impedance Measurement of Lithium-Ion Batteries, IEEE Transactions on Circuits and Systems I: Regular Papers, 2024 (under review)
3. J. Sihvo and T. Roinila, Pseudo-Random-Sequence (PRS) Perturbation Signals for Non-Stationary System Identification, *IEEE Transactions on Industrial Informatics*, 2024 (under review)
4. J. Sihvo, T. Roinila and D. Stroe, Cell-Level Implementation of Current-Sensorless on-Board Impedance Measurements in Multi-Cell Li-Ion Battery Stacks, IEEE Transactions on Industry Applications, 2024 (under review)
5. M. Tran and T. Roinila, Online Impedance Measurement of Lithium-Ion Battery: Applying Broadband Injection with Specified Fourier Amplitude Spectrum, IEEE Transactions on Industry Applications, 2023.
6. M. Tran, J. Sihvo and T. Roinila, Internal Impedance in Determining Usability of Used Lithium-Ion Batteries in Second-Life Applications, IEEE Transactions on Industry Applications, 2023.
7. M. Tran, D. Stroe and T. Roinila, Ultra-Fast Temperature Estimation of Lithium-ion Batteries Through Impedance Measurements, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2024.
8. D.-I. Stroe, J. Sihvo and T. Roinila, Battery states monitoring and estimation using impedance identification techniques, Tutorial, in *IEEE Energy Conversion Congress and Exposition*, 2024.
9. M. Ahangar, M. Tran, T. Roinila, P. Rasilo and M.H. Shojaeefard, Cold-Weather Profiling of Lithium-ion Cell Using Hybrid Pulse Power Characterization, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2024.
10. M. Tran, L. Lignell, E. Santi and T. Roinila, Issues in Practical Impedance Measurement of Li-Ion Batteries, in *Proc. IEEE International Conference on DC Microgrids*, 2024
11. M. Tran, J. Sihvo, L. Lignell and T. Roinila, Implementation Techniques for Online Impedance Measurement of Li-ion Batteries, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2023.
12. J. Sihvo and T. Roinila, Current Sensorless Broadband Impedance Measurement Technique for Li-ion Battery Applications, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2023.
13. J. Sihvo, V. Knap, T. Roinila and D.-I. Stroe, Adaptive configuration of generalized nonlinear ECM of Li-ion batteries based on impedance measurements and DRT analysis, in *Proc. European Conference on Power Electronics and Applications*, 2023.
14. L. Lignell, M. Tran and T. Roinila, Broadband Methods for Battery Management Systems: Online Impedance Analysis, in *Proc. Automation Seminar*, 2023.
15. M. Tran, T. Roinila and J. Markkula, Realtime Internal-Impedance Measurement of Lithium-Ion Battery Using Discrete-Interval-Binary-Sequence Injection, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2022.
16. M. Tran, T. Messo, R. Luhtala, J. Sihvo, T. Roinila and J. Markkula, Used Lithium-Ion Batteries in Second-Life Applications: Feasibility Study, in *Proc. IEEE Energy Conversion Congress and Exposition*, 2022.

## 5.4 Lifetime of li-ion battery

### 5.4.1 Problem/challange/need description

Li-ion batteries age as a result of usage and over time. As the battery ages its usable capacity decreases and internal resistance increases, which degrade battery performance in the application. At some point the performance of the degraded battery no longer meets the application requirements and the battery reaches its end of life in that application.

Battery ageing can be divided to calendar ageing, that occurs as a function of time, and cycle ageing, that occurs as a function of battery usage. The ageing rate of Li-ion batteries is affected by degradation stress factors that are temperature (T) and state of charge (SOC) for calendar ageing, and depth of discharge (DOD), operating temperature (T), middle state of charge (mid-SOC), and charge and discharge rates (C-rate) for cycle ageing.

The effect of different degradation stress factors on Li-ion battery ageing and lifetime has been experimentally studied and reported in scientific literature. However, as there are several Li-ion battery chemistries that behave in slightly different ways and these chemistries are constantly developing, there is a need for experimental data on the effect degradation stress factors on the lifetime of state-of-the-art Li-ion battery chemistries.

Some stress factors, such as operating at low temperatures, are particularly relevant for non-road mobile machinery (NRMM) operated in Nordic conditions. Another interesting stress factor is the charging rate because fast charging during the day would enable all-day operation with a smaller battery. Especially fast charging at low temperatures has been found to be detrimental for Li-ion batteries, but a better understanding of the phenomenon would be valuable.

### 5.4.2 Approach and solution

Two Li-ion battery degradation stress factors were selected to be investigated experimentally: 1) operating temperature, and 2) charging rate. An experimental test matrix to study the effect of operating temperature and charging rate on Li-ion battery lifetime was designed, including:

- 2 Li-ion chemistries: NMC811 cells (LG INR21700-M50LT) and LFP cells (LithiumWerks ANR26650M1B) were selected for testing. The selected NMC811 cells have the latest commercially available NMC cathode and high energy density. The selected LFP cells have good power properties (4C charging and discharging) and high cycle life. NMC is currently the most widely used Li-ion chemistry in electric vehicles and industrial applications, whereas LFP is rapidly increasing its share in many applications.
- 4 temperatures: -10 °C, 0 °C, RT, 35 °C. -10 °C was selected to study how cycling, especially charging the cells in sub-zero temperatures affects their lifetime. 0 °C is a common minimum charging temperature for Li-ion cells and therefore and interesting testing temperature. Room temperature (RT) is a reference temperature, and testing at 35 °C shows how elevated temperature affects the battery lifetime.
- 3 charging rates: NMC cells were charged with 0.3C, 0.7C and 1C, and LFP cells were charged with 1C, 2C and 4C. The discharge rates were 1C for NMC cells and 2C for LFP cells.
- Idle cells to detect calendar ageing. Some idle cells were positioned in the testing temperatures for the duration of the cycling to detect what part of ageing is calendar ageing and what part is cycle ageing.

Reference performance tests were carried out between the cycling tests to observe battery degradation:

- Capacity tests: Show the decrease in available capacity as a function of ageing.
- Electrochemical impedance spectroscopy (EIS): Show the increase of cell impedance as a function of ageing.
- Battery electrical characterization tests: Provide data for parametrizing an equivalent circuit model (ECM) for the battery. As the characterization is repeated at different stages of battery cycling, the effect of battery ageing on the model parameters can be investigated.

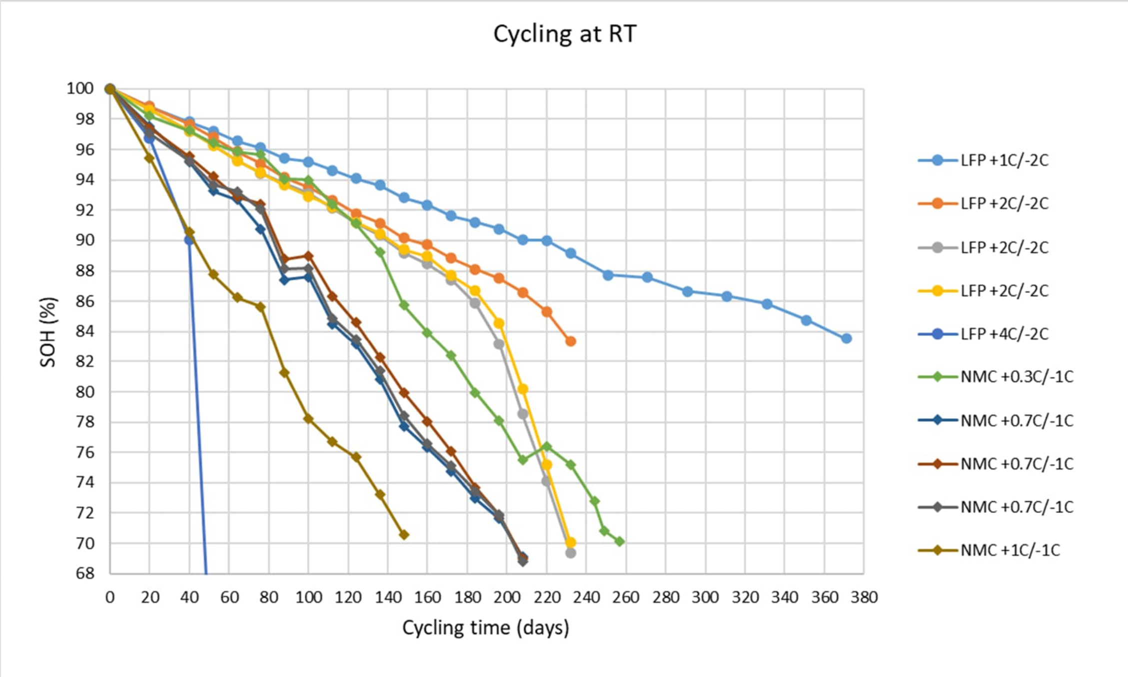



*Figure 1: Cycle ageing test results at room temperature (RT). Five cells from both NMC and LFP chemistries were cycled.*

Combining the results of the cycle ageing tests where the studied stress factor is varied enables forming an experimentally validated degradation stress factor model for the investigated battery chemistry. In this case temperature and charging rate stress factor models were formed for NMC and LFP chemistries.

The degradation stress factor models can be applied to estimate the battery degradation rate in the application when either measured operational battery data or the estimated duty cycle and usage conditions in the application are known. The variation of each stress factor and its effect on battery degradation rate can be analyzed from the application data. By combining the effect of different stress factors, an estimate of the battery's degradation rate and lifetime in the application is obtained.

### 5.4.3 Benefits and value

Experimentally validated knowledge on the effect of different stress factors on Li-ion battery lifetime enable:

- Estimates on how long the battery would last in the specific operating conditions. This helps planning the life cycle of the machine and its battery.
- Support for battery technology selection and battery dimensioning during the design phase of the machine. Correctly selected and dimensioned battery technology ensures sufficient performance and minimizes the costs.
- Optimization of the battery usage to achieve longer battery life and thus lower costs and lower environmental footprint. When the stress factors causing rapid degradation in the application are identified and mitigated, longer battery life can be achieved.

### 5.4.4 Publications

1. S. Jenu, A. Hentunen, J. Haavisto, Experimental analysis on the effect of charging rate and operating temperature on Li-ion battery cycle life (Journal publication, in writing)

## 5.5 Dimensioning of batteries and charging of NRMM fleet within industrial microgrid

### 5.5.1 Challenge and the needs

Electrification is the most potential means of decarbonising non-road mobile machinery (NRMM). However, the introduction of battery-electric powertrains is a more profound change than just switching from one power source to another. Batteries, charging, the electric grid and electricity purchase from markets bring new challenges and possibilities for NRMMs, and optimisation and modeling of the machines, charging and electricity delivery infrastuctures are needed.

The battery is the most expensive component of the battery-electric powertrain. Besides being a financially non-optimal solution, over-dimensioning the battery adds extra weight on the NRMM. However, the high utilization rate of mobile machinery, and availability and power requirements cannot be met without a proper battery capacity. Furthermore, recharging a battery is slower than refuelling a diesel tank, and the productivity level of a battery-powered NRMM may become lower than that of the corresponding conventional machine, if not properly considered. As the battery technology evolves and high-power charging becomes standard, the performance of battery-electric machinery improves.

The high-power charging may stress the electric grid, if the charging is not arranged optimally. The electrification of entire machinery fleets in remote locations may create the need to invest in electricity delivery infrastructure in the industrial site and also in the supplying grid. Supply grid expansions for remote locations are time-consuming and expensive, and therefore on-site electricity production in the industrial site becomes interesting alternative for supply grid expansion. Such remote locations include mining and forestry sites. The entire system consisting of the machinery fleet, charging infrastructure and the electric grid should be analysed and dimensioned to reach the techno-economically most viable solution. Energy management of an industrial site becomes a challenge, because the electricity balance between charging loads and supply from solar and wind power plants and limitted supply grid capacity may not be guaranteed. Therefore, a stationary battery system or a demand response solution of charging loads (e.g. recharging moment of battery swapping) should be dimensioned from energy management perspective.

### 5.5.2 Approach and solution

The operations of the machinery fleet were simulated. A simulation platform used for on-road vehicles was enhanced with further features to enable analysis of non-road mobile machinery. The simulation platform includes the potential driving routes, charging options, and machine models. The energy consumption of the machines consists of the energy of traction and the energy required for completing machine-dependent tasks such as lifting, drilling, cutting, spraying etc. The traction energy is modelled by a longitudinal dynamics model and the working tasks are modelled by predefined power consumption data. Prior to the simulation, a machine-dependent schedule is formed to model the mission of each machine. In this manner, no predefined duty cycle for the powertrain is required, instead, the machine tries to complete the predefined list of tasks as efficiently as possible. The driving speed of the machine depends on the speed limitations and the characteristics of the driving route as well as the capabilities of the powertrain.

The simulation approach enables formation of various powertrain options for the machine. Battery data, including information on the capacity, chemistry, weight, C-rate, and efficiency can be specified for each machine. In addition, hybrid power options, e.g. the inclusion of fuel cells or diesel generators is possible. Recharging of the batteries can be arranged at specified locations or as dynamic recharging along specified segments of the operational route. The charging power can be controlled both via the infrastructure specification as well as based on the battery specifications. Rules for when and where to charge, e.g. based on the battery state-of-charge can easily be set up.

The simulations were demonstrated with a use case for open-pit mining machinery. The modelled machine types were drilling machines and large dumpers. The mobility requirements for the machine types were very different, whereas the dumper drives long distances each day, the drilling machine use relatively little energy for traction as compared to the drilling action. The high requirements on utilization of the drilling machine made it very difficult to operate based on fast charging only. The battery-electric powertrain turned out to be much more viable for the dumper despite its weight of 600 tons. The productivity level can be maximised through dynamic charging on uphill segments without adding too much costs to the overall system.

The high power charging standardisation roadmap was created.

The energy management of fully electrified underground mine was modelled and optimized to meet power balance requirements. Three different geographical locations (Finland, India and Canada) was considered to model variations of on-site solar power and remote wind power variations. The load demand consisted of ventilation, crushers, lights and charging loads of drills, bolters and loaders. The energy management was realized by a day-ahead forecast of 36 hours in rolling window basis for a complete example year. Linear optimization was applied for solving the energy management how to charge/discharge the stationary battery storage. Feasiable solutions for the three locations was search by dimensioning solar and wind power, stationary battery and supply grid capacity by utilizing the energy management. Stationary battery storage is required for power balancing when the demand exceeds the power supply, the supply grid capacity is exceeded by the load demand, or solar and wind power is exceeding the load demand. The study assumed non-flexible electricity demand in the mine, but the battery swapping would potentially provide opportunity for optimization/scheduling the recharging of batteries as well.

The dimensioning of the stationary battery system is dependent on the correlation between the load demand and power supply in hourly level. Close to equator where the seasonal solar power variations are relatively minor, the battery is basically dimensioned for the balancing daily net-load variations to charge excess power when available (day-time) and to supply power to loads when the system has deficit of energy (night-time). In the northern hemisphare the situation is more complex, because the mix of solar and wind power is essential to guarantee good enough power availability and to minimize the need for long-term (weeks or months) energy storage. If good enough power availability may not be guaranteed with the mix of solar and wind power alone, then the alternative storage solutions like hydrogen or synthetic fuels should be considered, which may be utilized as such in the NRMMs in addition by providing opportunity for sustainable flexible on-site power generation and backup power supply.

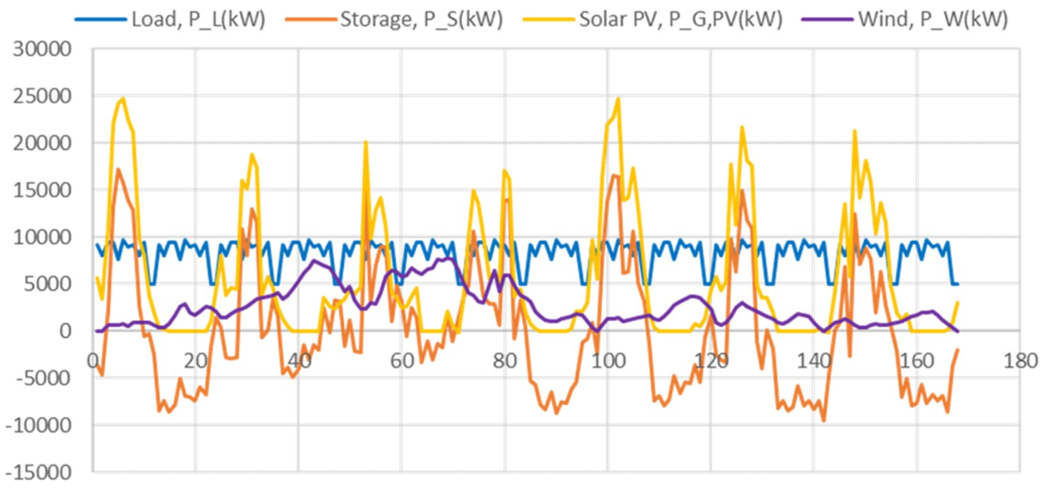



Figure 1. Example of energy management of electrified mine with on-site solar power, remote wind power and on-site stationary battery in supply grid limitted case (wind power capacity may not exceed the grid capacity about 8 MW).

### 5.5.3 Benefits and value

- Virtual evaluation of different powertrain options with simulations
- New operational possibilities and cost savings with MCS
- Techno-economical optimisation of battery types and configurations, as well as charging strategy

- Understanding and affecting the MCS standards from NRMM point of view
- Optimum energy management and microgrid dimensioning

### 5.5.4 Publications


1. S. Das, Feasibility analysis of distributed generation and storage combined energy balance management of industrial microgrid, MSc thesis, Tampere University, 2023.
2. S. Das, N. Riaz, S. Repo, Strategic electrification feasibility assessment through distributed generation and energy storage dimensioning for industrial microgrids, to be submitted to Cired conference, 2025.

# 6 Theme 2: Mobile Working Machines in Digitalized Worksites

## 6.1 Vision-based control of heavy-duty 6 DOF manipulator

This theme considers heavy-futy 6 DOF mqanipulator operation on wheeled platform subject to arm quasi-static flexibilities (inaccurate FK/IK) and platform center of gravity changes (arm motions/uneven ground)

### 6.1.1 Problem

The challenge of whole-body motion estimation and control of a heavy-duty 6-degree-of-freedom (DOF) manipulator on a floating base is complex, especially when considering link deformations. These deformations significantly impact the precision and stability of the manipulator's movements, leading to inaccuracies in Forward Kinematics (FK) and Inverse Kinematics (IK). Consequently, it is necessary to develop advanced observer algorithms and robust control strategies. For industrial applications, ensuring accurate motion control of heavy-duty manipulators is crucial. The floating base adds complexity, necessitating a comprehensive motion estimation approach that accounts for the entire system's dynamics.

Key research areas include developing advanced sensor fusion techniques, integrating data from accelerometers, gyroscopes, Leica laser tracker 6 DOF, and camera for a comprehensive picture of the manipulator's state. This integration helps the algorithms account for link deformations and other disturbances more effectively. Additionally, adaptive control strategies dynamically adjust control parameters in response to system changes, maintaining precision and reliability. Whole-body motion estimation and control of a heavy-duty 6DOF manipulator on a floating base involves addressing link deformations and dynamic system nature. Advanced observer algorithms, sensor fusion, adaptive control contribute to significant progress, enhancing the capabilities of industrial manipulators for greater precision, efficiency, and reliability.

### 6.1.2 Approach and solution

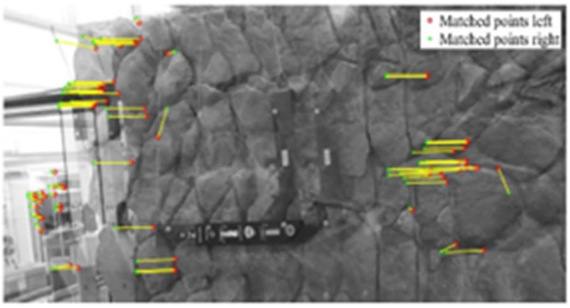
To address the challenge of whole-body motion estimation and control of a heavy-duty 6-DOF manipulator on a floating base, it is suggested to integrate measurements from both exteroceptive (e.g., cameras) and proprioceptive (e.g., encoders) sensors. Consequently, a stereo camera and an Inertial Measurement Unit (IMU) are attached to the Tool Center Point (TCP) to provide task space information, alongside joint space measurements obtained from encoders. Moreover, a Leica laser tracker 6 DOF is used to build and calibrate a better forward kinematics (FK) model of the non-rigid long-reach manipulator, enhancing the performance of the vision-based controllers.

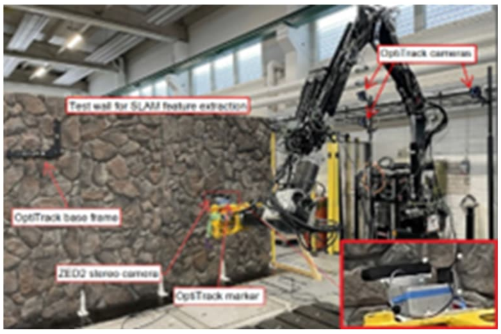
This integration of sensor data aims to create a comprehensive understanding of the manipulator's state, accounting for both the external environment and the internal dynamics. The stereo camera offers detailed visual information about the surroundings, which is crucial for tasks requiring high precision and interaction with objects. Meanwhile, the IMU provides critical data on the orientation and movement of the TCP, enhancing the system's ability to detect and compensate for any deviations or disturbances. By combining these exteroceptive sensors with the proprioceptive measurements from encoders, which track the position and velocity of each joint, the control algorithms can achieve a more accurate and robust motion estimation. This holistic approach ensures that both the external and internal factors affecting the manipulator's performance are considered, leading to improved stability and precision.

To leverage the advantages of measurements obtained from the IMU and stereo camera, novel algorithms have been developed for visual-inertial navigation systems. These estimation algorithms fuse data provided by the IMU and stereo camera to accurately estimate the end-effector's pose. Subsequently, new task space control techniques have been designed to control the end-effector using the estimated pose. By utilizing the estimated pose, the new task space control techniques can precisely control the end-effector, ensuring it follows the desired trajectory with high accuracy. To evaluate the performance of the proposed algorithm, we applied it to real-world datasets that we gathered, ensuring its relevance to actual scenarios. The experimental full 6 DOF robotic setup is shown in figure (1), comprising commercial heavy-duty hydraulic manipulator arm (HIAB033) equipped with in-house build spherical 3 DOF wrist and a Vahva grapper with absolute encoders at each joint Ethercat interfaced to real-time robotic control system running in Beckhoff and TwinCat 3. Exteroceptive system is an eye-in-hand low-cost ZED2 stereo camera with 16-bit tactical grade 6 DOF IMU (ADIS 16475-2). In addition, OptiTrack Prime 17W motion capture system is serving as ground truth system.

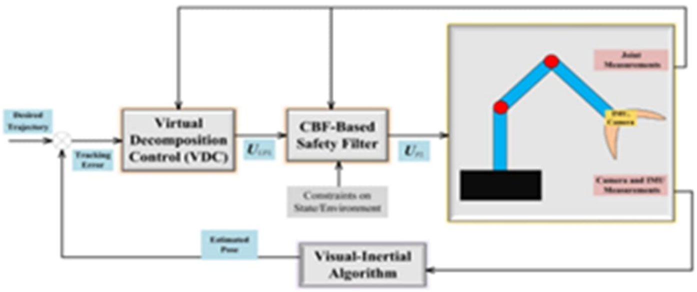
The integration of visual-inertial navigation systems into heavy-duty 6-DOF manipulators on floating bases addresses several challenges associated with dynamic and unstructured environments. The ability to accurately estimate and control the end-effector's pose in real-time enables the manipulator to adapt to changes and disturbances, maintaining performance and reliability even under unpredictable conditions. This adaptability is crucial for tasks in environments where the manipulator must interact with moving objects or compensate for shifts in its own base.

In summary, the development of novel algorithms for visual-inertial navigation systems and the subsequent design of new task space control techniques represents a substantial improvement in the field of robotics. By fusing data from IMUs and stereo cameras to estimate end-effector pose, and utilizing this information for precise control, these innovations lead to significantly increased tracking accuracy. This progress not only enhances current applications but also expands the potential use cases for heavy-duty 6-DOF manipulators on floating bases, paving the way for more advanced and reliable robotic systems.



(a)



(b)

Figure 1. (a) The experimental setup; (b) Sketch of the proposed vision-based controller.

### 6.1.3 Benefits and value

Nowadays, industrial robots are mostly blind, requiring extensive preprogramming to execute a sequence of tasks. If something changes in the environment, they often fail to perform the task. The use of exteroceptive sensor-based controllers, such as vision-based control, can significantly reduce the amount of tedious preprogramming needed, which is highly sensitive to errors and environmental changes. This approach enhances the robots' ability to adapt to new conditions, thereby promising they can handle more complex tasks effectively and with greater reliability.

By incorporating technologies like VSLAM (visual simultaneous localization and mapping) or visual servoing, robots become markedly more flexible and adaptable. These advanced control systems enable robots to autonomously identify and locate their targets, or objects of interest (OOIs), which is essential for performing intricate tasks in dynamic and unpredictable environments. This increased flexibility allows robots to operate "in the wild," handling real-world situations with greater autonomy and precision. As a result, the potential applications of robots expand significantly in industrial automation, paving the way for a future where robots are integral partners in various complex human activities.

### 6.1.4 Publications

1. Hamed Hashemi, Seyed, and Jouni Mattila. "Task Space Control of Robot Manipulators based on Visual SLAM." arXiv e-prints (2023): arXiv-2302.

2.

S. Mohammad Tahamipour-Z., S. Yaqubi, and Jouni Mattila, ‘Computationally Efficient IMU-based Endpoint Position Estimation of a Flexible Manipulator with Transverse and Torsional Displacement Effects’, Accepted for 2024 IEEE 20th International Conference on Automation Science and Engineering, Bari, Italy, August 2024.

## 6.2 Universal trajectory generator for mobile working machines

### 6.2.1 Challange description

Safe control of mobile Working Machines (WM’s), has several technical and operational challenges. Mobile WMs, commonly used in industries like construction, agriculture, and mining, operate in dynamic environments and perform demanding tasks such as lifting, digging, and material transportation. These machines often work in confined spaces and close to human workers, necessitating high standards of safety and precision in their control systems. A significant need is generating control trajectories for WM’s such that the safety of the system is mathematically guaranteed. This way, we can ensure that our control logic always generates inputs that prevent a mobile working machine enter unsafe zones. Safety controllers used as safety filters can guarantee the safety of WM’s both at a highly automated level and when operated by a human operator.
In summary, our main goal in this task is to find generic methods that can generate safe control inputs for the WMs concerning different types of constraints, such as control input constraints, time constraints, and try to improve the long-term performance of a WM while preserving safety.

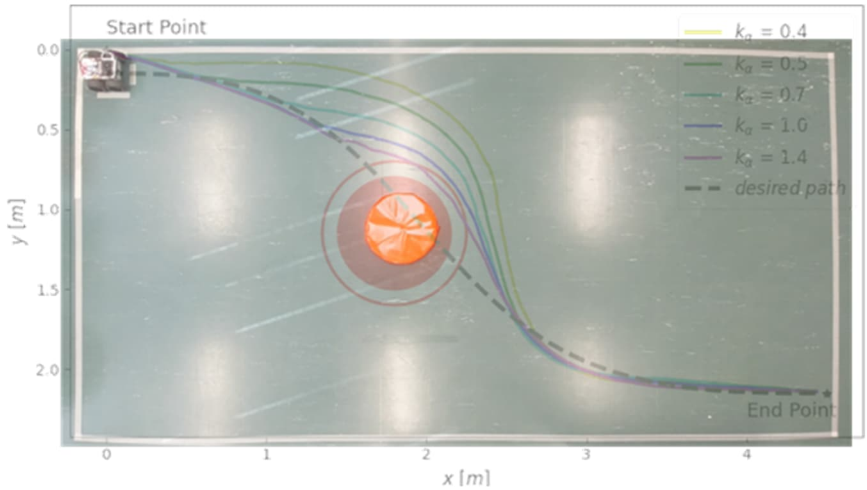
### 6.2.2 Approach and solution

To address the need for safe control in mobile working machines (WMs), our research integrates several advanced control techniques that ensure safety while improving performance and reducing conservatism in decision-making. At the core of our approach is the concept of **Control Barrier Functions (CBFs)**, which mathematically guarantee that the state of a dynamical system remains in a safe set. CBFs are Lyapunov-like functions that take the system’s state vector as an input argument and produce a scalar output—positive when the system is in a safe state and negative when it is in an unsafe state. With a properly designed CBF for the motion of a WM, the system can be controlled using an optimization-based controller, which solves a quadratic program (QP) at each control time step. Given the availability of fast QP solvers, CBF-based

controllers can operate in real-time. In addition to their direct control applications, CBFs can also function as **Safety Filters (SFs)**. These filters take nominal control inputs and the system's state as inputs, and then adjust the control actions to ensure safety while staying as close as possible to the original control inputs. Furthermore, CBFs can be constructed algorithmically to account for input constraints and even actuator dynamics, ensuring that safe control is maintained despite hardware limitations. Finally, combining CBFs with **Model Predictive Control (MPC)** allows us to capitalize on the strengths of both methods. This approach enables the generation of safe control actions while also considering the longer-term behaviour of the system, optimizing for both immediate safety and future performance.
Below, we summarize the key methodologies we at Autonomous Mobile Machine research group have developed:

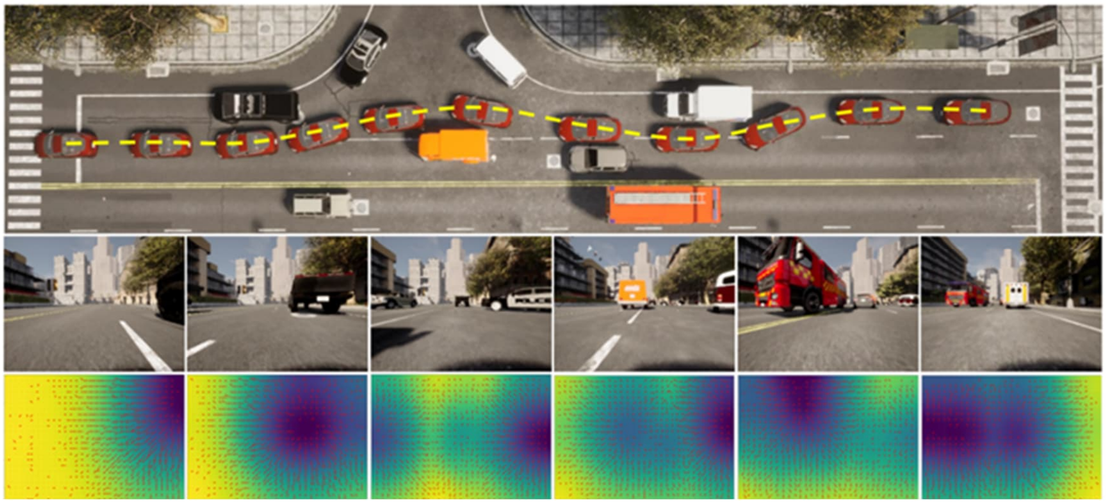
#### 6.2.2.1 1. Reactive Safe Path Following Using CBFs (ICCMA 2022)

This approach focuses on ensuring the safety of mobile robots performing reactive path-following tasks, particularly in differential drive robots. By combining Control Lyapunov Functions (CLFs) with Control Barrier Functions (CBFs), this method achieves both stability (path following) and safety (collision avoidance). The key innovation is proposing a CBF that enables first-order CBFs, simplifying control computations and making the approach feasible for real-time applications. As a result, this method is well-suited for mobile WMs, enabling them to avoid obstacles while maintaining their path in static environments.



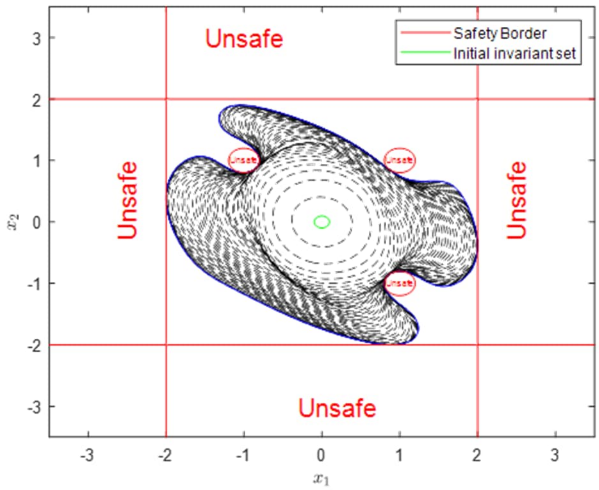
6.2.2.2 2. Vision-Based CBF for Enhanced Environmental Awareness (ICRA 2023)

6.2.2.3 This solution introduces a Vision-based Control Barrier Function (V-CBF) framework designed to ensure robot safety in previously unmapped environments. The approach uses RGB-D images to generate CBFs in runtime that dynamically adapt to various obstacles, making real-time safety guarantees possible. Conditions are applied over the image space, with linear and angular speed controls to handle kinematics. A conditional Generative Adversarial Network (cGAN) converts image data into CBFs. The approach is validated using an autonomous car in the CARLA simulator, demonstrating its ability to navigate safely in complex and unknown settings.



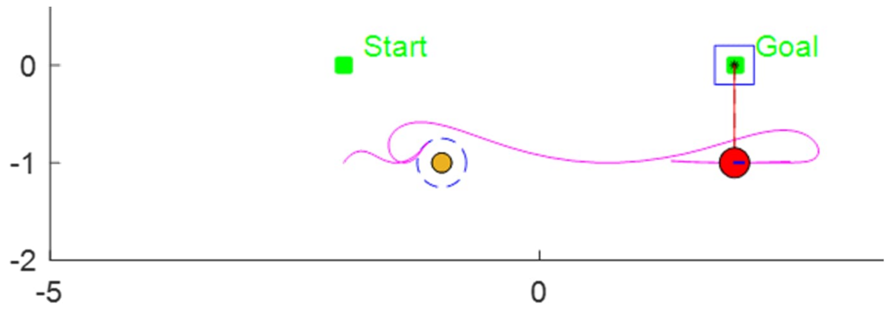
6.2.2.4 3. Convex Synthesis of CBF under Input Constraints (IEEE Control Systems Letters 2023)

One key challenge for mobile machines is adhering to input constraints imposed by hardware, such as actuator limits. This work addresses the synthesis of CBFs that respect these constraints while still ensuring safety. By constructing barrier functions that operate within the machine's actuator limitations, we prevent infeasibility in real-time optimization-based control. This ensures that the control actions remain both feasible and effective, reducing the risk of system failure due to actuator constraints.




6.2.2.5 4. Model Predictive Control Barrier Functions (MPCBF) for Optimal Safety (ACC 2024)

To address the conservatism inherent in traditional CBF methods, we developed a framework combining Model Predictive Control (MPC) with CBFs, termed Model Predictive Control Barrier Functions (MPCBF). This hybrid approach predicts future states over a predictive horizon and enforces safety constraints in a way that reduces overly cautious decision-making. By doing so, it allows for more aggressive yet still safe control behaviours, significantly improving operational efficiency. This is particularly beneficial for complex tasks like material handling or load lifting.




#### 6.2.2.6 5. High-Order CBF for Nonlinear Systems (under review 2024)

Mobile working machines often have nonlinear dynamics, particularly those with articulated steering mechanisms. In this research, we propose a High Order Control Barrier Function (HOCBF) framework that effectively handles these nonlinearities. By integrating actuator dynamics with unicycle dynamics, this approach ensures safety while maintaining high performance through the use of Control Lyapunov Functions (CLFs). This method is particularly well-suited for machines with complex actuator dynamics, such as hydraulic actuators.

#### 6.2.2.7 6. OGM-Based CBF for Safe Navigation in Occupancy Grid Maps (under review 2024)

This research explores an Occupancy Grid Map (OGM)-based CBF approach for safe navigation in unknown or partially known environments. By continuously updating the occupancy grid based on sensor data, this method dynamically adjusts the machine's movements as it perceives new obstacles or environmental changes. This capability makes it ideal for mobile machines operating in semi-structured or unstructured environments like construction sites or agricultural fields, ensuring both safety and adaptability.

#### 6.2.2.8 7. Sum of Squares Optimization for Input-Constrained CBF Synthesis (work in progress)

In this work, we introduce a Sum of Squares (SOS) optimization technique to improve the CBF synthesis for systems with  input-constrains. This method allows for systematic design of CBFs that account for strict input constraints, ensuring feasibility across a wide range of actuator dynamics. It guarantees safety even when operating under stringent control input limits, making it particularly useful for systems facing severe energy or force constraints.

### 6.2.3 Benefits and value

Our proposed solutions offer a robust framework for ensuring the safety of mobile working machines and autonomous systems operating in static environments. By addressing the integration of vision sensors, the impact of actuator dynamics, and the management of input constraints, we have developed a suite of methods that tackle safety challenges in control systems. The benefits of our solutions can be summarised as follows:

1. All our proposed solutions are suitable to be used online. This ability comes from the fact that CBFs provide us with simple rules that can generate safe control inputs using quadratic programs.
2. We can use CBFs on top of vision and Lidar sensors to directly relate sensor input to safe control devising.
3. We can construct CBFs for systems with actuator dynamics or actuator delays and ensure safe control devise for the system.
4. We have a solution to make MPC less conservative and shorten the horizon by combining MPC with CBF.

In summary, our solutions offer practical, real-time safety guarantees that are flexible, sensor-integrated, and capable of handling complex system dynamics, making them highly suitable for modern industrial applications.

### 6.2.4 Publications

1. "Reactive Safe Path Following for Differential Drive Mobile Robots Using Control Barrier Functions." Ebrahimi Toulkani, Naeim et al, ICCMA. 2022.
2. "Safe Control using Vision-based Control Barrier Function (V-CBF)." Abdi et al. ICRA, 2023.
3. "Convex synthesis of control barrier functions under input constraints." Zhao, Pan, et al. IEEE Control Systems Letters 2023.
4. “Model Predictive Control Barrier Functions (MPCBF): guaranteed safety with reduced conservatism and shortened horizon,” Abdi et al, ACC 2024.
5. “Safe Control of Nonlinear Systems with Affine Actuator Dynamics: A High Order Control Barrier and Control Lyapunov Functions Approach”, Ebrahimi Toulkani, Naeim, et al. (2024, under review).
6. “Safe Control using Occupancy Grid Map-based Control Barrier Functions (OGM-CBF)”, Raja, Golnaz, et al. (2024, under review).
7. “Input-Constrained Control Barrier Certificates Synthesis via Sum of Squares Optimization”, Ebrahimi Toulkani, Naeim, et al (2024, in progress)

## 6.3 Situational awareness for safe human machine co-existence

### 6.3.1 Need description

When a vehicle or moving work machine is operating, one of its key features is its accepted safety level; companies want to minimize accidents, and especially accidents involving humans. The reasons for this can be found from legislation, but low accident rate has also become a generic measurement of the quality, how the company is managed.

The key functionality needed is automatic environment perception and automatic preventive actions, in case another vehicle or human is found from the current risk zone of the vehicle or work machine. This approach applies to vehicles/machines controlled on-board from cabin, remotely via some kind of remote interface, or automatically so that controls are given by on-board computers executing a mission.

Especially in outdoor environments the sensors (cameras, lidars and radars) have many difficulties to differentiate reliably natural features from humans that appear in various poses and clothing – and often partly covered by obstructions. The job is not made easier by the hugely varying environmental conditions:  from pitch black night to low hanging sun shining right into camera, or from dense fog to wind-blown dust or heavy snowfall. Thanks to these difficulties, very few perception sensors have safety rating for outdoor use. Even more difficult game is the development of object recognition algorithms, that would be safety acceptable.

Typically the collision safety of a vehicle/machine has been the drivers obligation. With remotely operated or especially with autonomous vehicles/machines the collision safety has to be an approved product feature. Otherwise it will be very hard to sell.

### 6.3.2 Approach and solution

The solution is based on 3D sensors (like lidar, stereocamera, possibly a radar as well). Also all the sensor detections are handled in global coordinates. The fundamental functionality is to detect the motion of objects during the whole period they are in the observation area of the sensors. Another key feature is, that the method does not try to recognize objects – this way one problematic functionality, e.g. reliable object recognition, can be avoided.

The solution has been explored in forest environment for forwarder machine use, and in container yard for straddle carrier use. In both cases the sensor was a high resolution 360 degree lidar. For ground removal the Progressive Morphological Filter and its approximate variation were used. VTT has found these algorithms to function well. It must be noted that the algorithm of the basic PMF filter is well analysable, e.g. it does not contain learning features, nor neural networks.

The log forwarder has a 20 meter safety zone, when it is working in the woods, it must stop operating if a human comes closer. The monitoring has traditionally been drivers responsibility, but additional sensing would help the driver. Especially if the machine is operated remotely, the operator will have a more reduced understanding of the surroundings of the machine, and a complementary system for monitoring safety zone violations would be very welcome.

The image below shows experimental lidar data recorded from a typical working site of a forwarder. The ground removal algorithm has analysed all the points. Green points were categorised as belonging to the ground, and can be removed from further analysis. Red points contain potentially various objects. One object is emphasized with a cylinder; a walking human, located closer than 20m to the lidar.

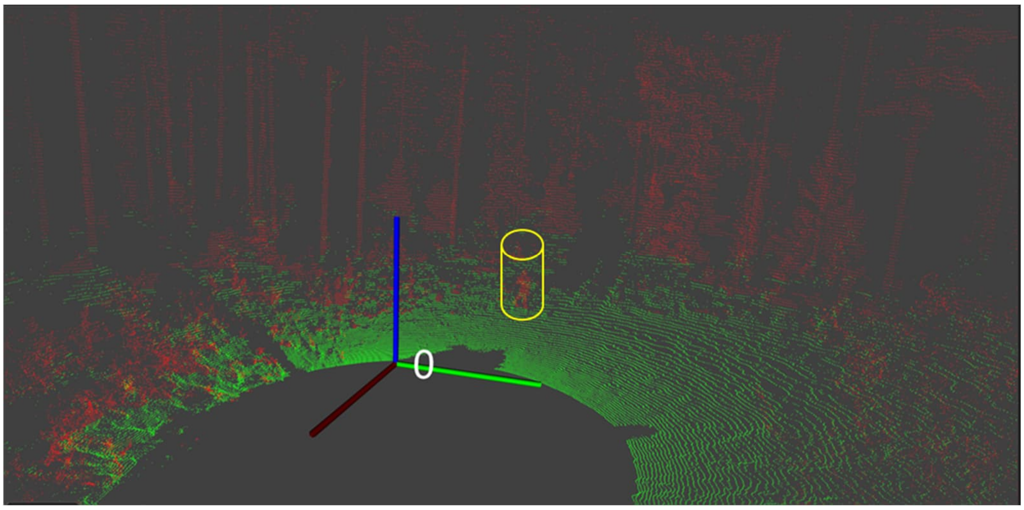



Figure 1 A lidar point cloud from forest. Green points are categorized as ground. Moving objects are searched from the red points. Yellow cylinder shows a human moving in the area. The orthogonal red, green and blue axes are the coordinate system of the lidar.

Similar tests were made in container handling environment. Due to the even asphalt ground in the area, ground detection and removal is straightforward. Humans were also easier to distinguish in this environment, since the other shapes in the environment - containers and vehicles – have clear vertical boundaries.

The method requires handling all sensor detections in global coordinates. The location and orientation of the vehicle/machine can be achieved with the help of GNSS system, which can be supported with correction services like RTK. Another approach is to utilize so called SLAM approach, where the vehicle location is calculated by utilizing previously measured environmental features detectable with the perception sensors of the vehicle. Therefore it is not demanding to continuously maintain the global location and orientation of the vehicle, which the allows the tracking of the surrounding objects also in global frame.

### 6.3.3 Benefits and value

The developed method is a human proximity detection for vehicles and moving machines, <u>allowing analysis of its detection reliability and system safety</u>, thus paving way for acceptable safety systems.

Guaranteed safety performance is a must before factories, pulp mills, container terminals etc. accept remotely operated or autonomous machines in their premises among humans and other traffic.

### 6.3.4 Furher documentation

1. P.Peussa, M.Jokela, T.Miekkala, K.Raunio, J.Berger, Invention disclosure DRAFT27765: Puukuormatraktorin turva-alueen valvontakonsepti.

# 7 Theme 3: Digital solutions for autonomy and electrification

## 7.1 Information exchange architectures to enable use of WM data

### 7.1.1 Problem description

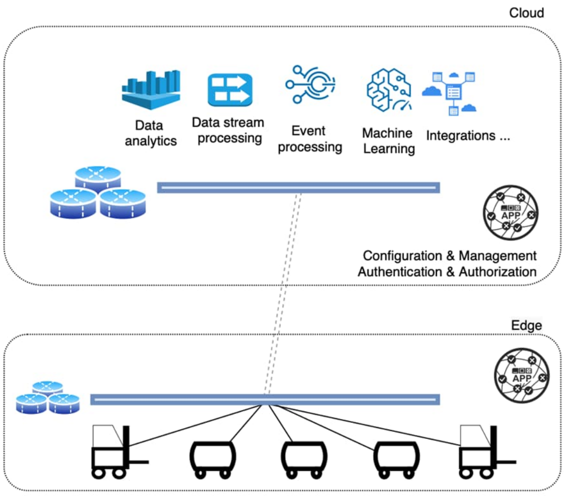
What kind of information exchange architectures are needed for WMs of the future to enable the use of data throughout the lifecycle in new, emerging applications? How can we develop secure and resilient information exchange to ensure the safe and efficient operation of WMs?

How can data and its sharing be managed in multiparty environments from WMs to heterogeneous edge and cloud platforms? How can interoperability of data be improved and facilitated to improve its utilization prospects and significantly automate, for example, the use of AI based methods?

How can different data architectures support data-driven business models?

### 7.1.2 Approach and solution

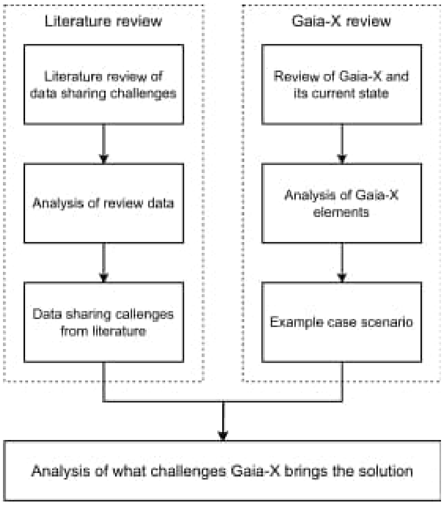
Apache Pulsar is studied as a scalable message broker architecture to deliver information needed for WMs to work autonomously in their working environment in a distributed manner also including cloud integration capabilities.

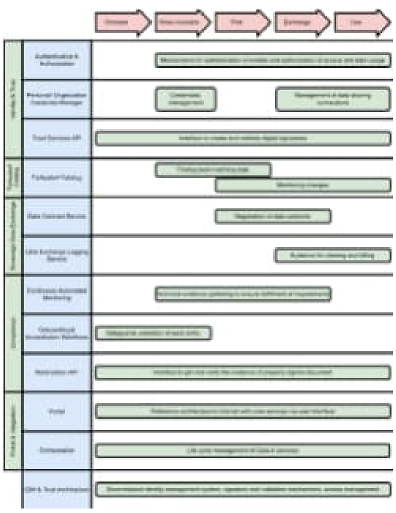



Through a literature review, 19 challenges of inter-organizational data sharing wereidentified. The review included 24 academic papers from the years 2017-2022. The papers were searched from two different databases, ACM and IEEE Xplore, using following search strings:

- IEEE: ("data shar*" OR "data exchang*") AND ("ecosystem" OR “inter-organization*” OR “across organization*” OR “between organization*” OR "dataspace*" OR "data space*")
- ACM: (“data sharing" OR "data exchanging") AND ("data ecosystem" OR “inter-organizational” OR “across organizations” OR “between organizations” OR "dataspace" OR "data space").

Secondly, the current state of development of Gaia-X architecture and federation services were reviewed and their capabilities to address the identified challenges were analyzed. The analysis showed that the architecture and the services improve the discoverability of heterogeneous data from different distributed sources and support the interoperability on the semantic level. The distributed nature of the architecture shifts the responsibility for securely storing data to the data owners/providers increasing their power to control their data. Moreover, the ability of data owners/providers to retain the control over their data is emphasized by making data sovereignty one of the most important design principles of the architecture. The architecture and the federation services facilitate data sovereignty through access and usage policies that can be negotiated automatic or semi-automatic way improving the efficiency of data sharing. However, the biggest identified weakness of the architecture is the lack of the technical enforcement of usage policies.



## 7.1.3 Benefits and value

Message broker based asynchronous communications spanning cloud to edge

- Apache Pulsar is scalable message broker with support for multiple broker clusters
- Pulsar geo-replication feature allows making robust messaging architecture spanning edge to cloud

Information exchange challenges

- The identified challenges were divided into 7 categories: cooperation, competition, data quality, data ownership, security, syntactic interoperability, and semantic interoperability.
- The challenges fall under three main themes: interoperability, data governance and business challenges. These findings clarified the needs of multi-actor environments regarding data sharing infrastructure.

Gaia-X architecture and federation services:

- Improve discoverability of heterogeneous data and interoperability on the semantic level
- Enable automated and semi-automated contract negotiations improving efficiency
- Facilitate data sovereignty through access and usage policies
- Lack technical enforcement of usage policies
- The distributed nature of the architecture shifts the responsibility for securely storing data to the data owners/providers

### 7.1.4 Publications

1. Kannisto, P., & Hästbacka, D. (2022, September 6–9). Data Autonomy in Message Brokers in Edge and Cloud for Mobile Machinery: Requirements and Technology Survey. 27th IEEE International Conference on Emerging Technologies and Factory Automation – ETFA (pp. 1-4). IEEE. https://doi.org/10.1109/ETFA52439.2022.9921693
2. Kannisto, P., Juntunen, T., Heikkilä, R., Vilkko, M., & Hästbacka, D. (2023, March 28–29). Communication Approach and Framework for Distributed Path Planning Optimization of Industrial Vehicles [Conference presentation]. Automaatiopäivät 2023, Helsinki, Finland.
3. Mätäsniemi, K., Kannisto, P., Hästbacka, D. Data sharing challenges in inter-organizational data ecosystems: A domain-agnostic literature review (Submitted journal article)

## 7.2 Autonomy levels in mobile machine applications

### 7.2.1 Need description

Mobile machines are undergoing a significant transition towards green, digital, and autonomous solutions that will revolutionize their design and operation. These vehicles and machinery are increasingly aimed to perform specific tasks without human intervention, relying on sensors to interpret the operational environment and artificial intelligence (AI) to make decisions based on the sensor data. This transition demands substantial resources and investments from both industry and research sectors

Fluent cross-sector collaboration is crucial in system-of-system types of operation, where multiple service and machine providers cooperate to achieve a higher mission. Given the diversity of operational contexts, ranging from open systems to closed systems and from repetitive and simple to complex tasks, a Level of Autonomy (LoA) framework provides guidance in aligning autonomy solutions to specific operational needs.

Many production sites have expanded over time, resulting in a mix of modern and legacy equipment, leading to missing interfaces, incompatible communication standards, and multiple software systems. Further, a lack of IT and AI expertise limit site operators' ability to identify and implement potential use cases themselves. Consider the following example where a mine operator aims to transition to a highly autonomous mining system. To achieve this, the operator must engage in detailed discussions with various mining machine manufacturers about the current and desired conditions at the mine site. It is crucial for mine management and designers to understand the limitations of the autonomous mining technology they plan to use, along with the new safety risks and requirements that come with higher autonomy levels. The physical mine design needs to be suitable for the integration of autonomous equipment, as well as potential combinations of autonomous, semi-autonomous, and manual equipment. Mine operators and vendor partners will equally benefit from a uniform LoA framework allowing them to make informed decisions and overcome confusion and inefficiencies that arise from using their own definitions.

### 7.2.2 Approach and solution

In this paper, we present a 4-dimensional framework for levels and elements of autonomy that are needed to efficiently develop and deploy autonomous solutions in various applications and environments.

Autonomy levels have traditionally been identified for single-machine capabilities on a task or function level, assessing these capabilities in a relatively narrow, task-oriented manner. For example, the SAE J3016 levels for driving automation range from Level 0 (no automation) to Level 5 (full automation), focusing on aspects such as driver control and vehicle operation. However, the growing ambition to achieve system-wide autonomy requires a broader perspective and introduces new considerations for assessing autonomy. Evaluating systems' autonomy levels solely based on single-machine functional dimensions, such as driving and manipulation, is inadequate. System-specific criteria are essential to properly assess autonomy at the system level. Our efforts strive for a 4-dimensional LoA framework (Figure 1), that allows a detailed and nuanced analysis of autonomy.

| | **D – Driving**<br>*(Machine)*<br>*Navigatingand/or moving from place to another* | **M – Manipulation**<br>*(Machine)*<br>*Interacting with and modifying objects* | **O – Operation**<br>*(Connected machines)*<br>*Performing tasks to single work processes as a machine group (fleet)* | **S – Mission**<br>*(System mission)*<br>*Several connected machine fleets perform tasks in different work processes to achieve an overall system goal* |
|---|---|---|---|---|
| **0**<br>**No automation** | **D0**<br>**Full manual control.** Lateral and longitudinal motion controller manually e.g. steering,braking, acceleration | **M0**<br>**Joint space control.** Individual joints controlled e.g. boom, bucket | **O0**<br>**Human based task management.** Machines are operating as individuals. Task management by humans, H2H communication | **S0**<br>**Human based mission management.** Human operators are the only source of situational awareness |
| **1**<br>**Operator assistance** | **D1**<br>**Unidirectional control.** Either lateral or longituinal motion, but not both, is controlled. Huvan provides inputs e.g. traction control | **M1**<br>**Cartesian space control.** End effector is contolled e.g. bucket, harvester head | **O1**<br>**Assisted task management.** Model based worksite. Machine control system gives task related guidelines for the operator of the individual machine. | **S1**<br>**Assisted mission management and situational awareness.** Providing real-time alerts for potential hazards, requiring operator attention |
| **2**<br>**Partial automation** | **D2**<br>**Bidirectional control.** Both longitudinal and lateral motion control possible. Limites exteroceptive capabilities e.g. 'blind autonomy' in mines | **M2**<br>**Configuration control.** Pre-configured motion trajectories, no exteroceptive sensors e.g. swing control in harvester | **O2**<br>**Automated task management.** Model based worksite. Machine control system gives task related parametres for the individual machine. | **S2**<br>**Enhanced situational awareness.** Integrating more advanced sensors and data to support automated functions and human supervision. |
| **3**<br>**Conditional automation** | **D3**<br>**External perception.** Machine has exteroceptive capabilities and can navigate in structured environments e.g. Y or V cycle in loaders | **M3**<br>**External perception.** Extension of level M2with exteroceptive perception e.g. obstacle detection during trajectory | **O3**<br>**External perception.** Every machine selects its next task depending on the state of the mission. E.g in mining, dedicated machine continue the preparation of a tunnel after the previous machine has completed its task, In a harbor an individual machine enters a charging station, when it is optimal considering the entire fleet. M2M communication | **S3**<br>**Automated Decision-Making.**<br>Algorithms to handle safety-critical decisions in real-time, with human override capabilities. |
| **4**<br>**High automation** | **D4**<br>**Navigation autonomy.** Simultaneous localization and mapping capabilities. Machines can navigate in semi-structured environments withlow level real time decision making capability e.g. autonomous haulage systems | **M4**<br>**Task autonomy.** Interaction with homogenous materials in semi-structured environment e.g. perception based pile characterization | **O4**<br>**Operation autonomy.** The individual machines can give instructions and train other machines (exchange information) based on the state and goal of the mission. | **S4**<br>**Comprehensive System Coordination.** Dynamic risk awareness. Different autonomous systems can work together safely. Mechanisms for safe automatic recovery after system stops or failures. |
| **5**<br>**Full automation, autonomy** | **D5**<br>**Machine autonomy.** Active localization, mapping and collision avoidance systems | **M5**<br>**Machine autonomy.** Interaction with heterogenous materials. | **O5**<br>**Fleet autonomy.** The mission itself is not well defined (e.g. the consecutive missions are different) and the fleet of the machines can redefine the mission for achieving improved performance (aka autopoesis). | **S5**<br>**Mission autonomy.** Dynamic risk assessment. System is capable of making safety-critical decisions without human intervention. Incorporating machine learning and AI to improve safety measures and adapt to new challenges. |
| | **Intelligent, self-governing, independent machine.** Machine can operate in any environment with minimal human supervision and intervention. Human in a role of supervisor. | | | |

Figure 1. LoA framework with 4 dimensions for work machine systems (modified from (Machado et al., 2021)).

Unlike models that solely focus on the system autonomy level, or individual machine autonomy this framework addresses both by including dimensions for driving, manipulation, operation and mission. These dimensions are crucial because even advanced systems may have components at lower autonomy levels. Relevant autonomy evaluation criteria should be categorized into the following four dimensions, each with its own scope, to provide guidance on autonomy considerations (Table 1).

Table 1. Elaboration of autonomy considerations in each dimension.

| **Dimension** | **Description** |
|---|---|
| Driving | - Single-machine functional dimension<br>- Encompasses considerations enabling individual machines driving autonomy |
| Manipulation | - Single-machine functional dimension<br>- Encompasses factors that enable individual machines to achieve manipulation autonomy (functions other than driving e.g. drilling, pick-up, lifting, task planning, and scheduling) |
| Operation | - Connected machines or a fleet composing of machines with individual autonomy levels executing single work processes (mining process, container |

| | |
|---|---|
| | handling, storage and transportation work process, logistic processes, construction / earth moving processes)<br>- Encompasses considerations necessary for orchestrating autonomous driving and manipulation of individual machines or an entire fleet<br>- For example: Manufacturing Execution System (MES) or Site-Execution-System (SES) with task-management, real-time monitoring, and automatic documentation for sites, control system in automated work processes like mines or container handling |
| Mission | - Several connected machine fleets perform tasks in different work processes to achieve an overall system goal autonomously<br>- Encompasses considerations required for business-wide (software) systems for managing safety, logistics, disposition, procurement, product and document management, fleet management as well as asset tracking |

The system / mission dimension emphasizes system-wide management considerations, especially for operational and business functions as well as for system safety measures. Using safety as an example, at every level, as autonomy increases, the complexity and sophistication of safety considerations in the mission layer also increase. The system's capabilities evolve to handle a wider range of scenarios autonomously while maintaining a high standard of safety. Therefore, we introduce new capabilities such as 'dynamic risk awareness', and 'dynamic risk assessment' (Figure 1) in higher system autonomy levels. Especially, systems that consist of sub-systems at different autonomy level require special attention.

The mission layer must take into account, but is not limited to, the following list of safety considerations, which demonstrates the increasingly importance of safety considerations at higher autonomy levels:

- connections and interlocking of safety functions in systems with different level of autonomy
- changes of machines' or sub-systems' operating modes or autonomy levels
- gathering and usage of Situational Awareness (SA) information from different systems for safety critical decision making
- safe start-up, shut-down, operational change or recovery after an (un-) intentional stop or based on real-time SA information
- systems capability of making safety-critical decisions without human intervention
- determining situations when human operator must confirm and approve safety-critical actions or changes in planned safety operations
- assigning responsible persons for safety in different operating modes and autonomy levels
- Layers of protection (primary, contingency and preventive) to manage any potential failure scenarios
- plans for human override capabilities and transitions
- operators must be trained continuously to understand and effectively use varying automation features

We highlight, that the presented mission domain considerations only describe safety-related autonomy issues. A complete LoA framework shall not neglect other business-related and system-wide autonomy capabilities, concerning for example logistics, disposition, procurement, product, and document management.

### 7.2.3 Benefits and value

By utilizing a 4-dimensional LoA framework, companies can systematically identify and prioritize areas that require attention to achieve their desired level of autonomy. Additionally, a framework not only facilitates the identification of technology requirements for individual machines to be able to operate within a swarm, but also aids in determining the optimal LoA for their systems, considering all existing constraints. Furthermore, it provides companies with insights into both current and future opportunities associated with various levels of autonomy. This understanding aids in evaluating investments in fully or partially autonomous systems, as it allows for a comprehensive assessment of their business value against the required level of investment. When incrementally implementing necessary measures to achieve the desired autonomy level companies can identify suitable partners to support them in their efforts. Vice versa, a LoA framework also empowers turnkey providers to offer suitable upgrading solutions by streamlining communication and collaboration, facilitating smoother interactions. Additionally, a LoA framework fosters cross-sector collaboration by establishing common terminology across the industry. By adhering to a uniform LoA framework companies and industry sectors can overcome inefficiencies that arise when using own definitions.

In the ultimate vision to which we hope to contribute by presenting a 4-dimensional LoA framework, autonomous systems, regardless of the domain, achieve seamless and efficient operation without human intervention. The goal is to enhance productivity, safety, and reliability across various industries. A comprehensive and detailed LoA framework plays an increment role in achieving this ultimate vision, by providing a structured and standardized approach to development, ensuring safety and reliability, and facilitating internal and external communication and adoption across various industries.

### 7.2.4 Publications

1. VTT public white paper (planned)

## 7.3 Data-driven diagnostics and prognostics models

### 7.3.1 Challenge description

To contribute to addressing current climate challenges, the automobile industry is making significant investments in the development of electric mobile working machines, including loaders, drilling and bolting rigs, and haul trucks. A critical aspect of these new technologies that requires attention is maintenance management, as existing models are primarily designed for fuel-powered engines. Therefore, it is essential to develop a maintenance strategy that optimizes the availability of heavy electric working machines while reducing operating and maintenance costs.

This study examines current maintenance strategies and planning for fuel engines and presents a maintenance model that optimizes strategies for electric mobile working machines using Markov decision processes. The model determines an optimal, cost-effective maintenance policy based on the machine’s condition and associated maintenance costs, specifying the appropriate maintenance actions to take. The effectiveness and implementation of this model were tested by solving differential equations and using policy iteration through MATLAB and Maple V.

The study introduces a novel method for determining transition probabilities and identifying the optimal maintenance policy, which suggests the most effective maintenance actions. By applying the policy iteration algorithm, the model determines the optimal maintenance actions and related costs for a machine in a specific state, aiding maintenance experts in their decision-making. Furthermore, the model developed in this study offers significant benefits to industries managing the maintenance of heavy electric mobile working machines, enabling maintenance experts to save both time and money by accurately determining when and what maintenance actions are necessary.

### 7.3.2 Approach and solution

The study is done using the existing literature on maintenance strategies and planning, technical books, gathering data and interviewing maintenance and mechanical experts from the corporations involving in the study. Additionally, Markov decision Process and Matlab were applied for the mathematical equation building and the simulation of failure and maintenance data.
First, a literature survey is done to see if previous studies were completed on the optimization of maintenance strategies of working machines using Markov decision process and how its could be applicable in the current study(The maintenance management of electrical mobile working machines). Second, the existing maintenance strategies, the selected machine under study and the analysis of the mathematical and the software use to accomplish the research work.
Third the data collection, the analysis of the new method for optimizing maintenance strategies is evaluated and discussed to show the benefits of applying the new maintenance technique.

Optimizing the availability of electrical mobile working machines means increasing the reliability and maintainability of the concern equipment and to achieve that an effective maintenance optimization model must be chosen. Existing literature uses a variety of mathematical techniques to analyze system behavior and to determine its current state, also, predict the next possible state. These learning methods include, Random Forest algorithm, Artificial neural network, Support vector machine, Bayesian network, Deep learning Fuzzy logic, Clustering, Markov modelling [20].The latest one The current research study will be conducted based Markov modelling, especially Markov Decision Process (MDP) as the main goals of the research consist of determining the state of the machine and the adequate action to implement, and how this action improve the state of the equipment with low cost.
A Markov chain is a stochastic process if it has the Markovian property: given any past event and the current state, the conditional probability of any future event does not depend on the past event. It can be expressed in this way.

### 7.3.3 Benefits and value

The new findings will enhance maintenance action planning and streamline the daily activities of maintenance operators. This will enable companies to manage their assets more effectively, improve the operational conditions of electric machines, and extend the lifespan of these assets. Additionally, the approach used in this study to resolve the matrix exponential function, based on the state transition model, can be applied in future research endeavors.

In earlier sections, it was explained that transition probabilities were resolved for matrices with two rows and columns, whereas the state transition model in this study requires more complex matrices with six rows and columns, incorporating both a transition rate matrix \( Q \) and a transition probability matrix \( P \). This method can be extended to linear differential systems in future research to determine transition probabilities. It also holds potential for computer scientists analyzing Markov decision processes, as the method has significant applications in the field of machine learning.

Furthermore, the Markov decision process applied in this research allowed us to identify the optimal maintenance action when equipment is in a specific state, helping maintenance operators reduce failure rates, minimize maintenance costs, and save time in asset management.

To further verify the model's effectiveness, additional development is required. The challenge of obtaining real data and the lack of participation from maintenance experts in interviews limited the opportunity to observe the actual operation of heavy electric mobile machines and the daily challenges faced by maintenance departments. As a result, the validity and reliability of the model could not be fully confirmed. Future researchers will need to test the model under real conditions using original data to ensure its accuracy and applicability.

### 7.3.4 Publications

1. Yao Kossonou Appoh, Jouko Laitinen and Kari T. Koskinen: Developing New Method for Optimizing the Maintenance Strategy of Electrical Mobile Working Machines And Reduce Operating And Maintenance Costs, using Markov Decision Process. WCEAM Conference in Ho Chi Minh city, Vietnam, 2024
2. Yao Kossonou Appoh, Developing New Method for Optimizing the Maintenance Strategy of Electrical Mobile Working Machines. Master thesis Tampere University 2023
3. E. Heikkilä, H. Kortelainen, J. Tervo, M. Vilkko, J. Laitinen and K. Koskinen. Electrification and Automation of Mobile Machines Call for Maintenance Development. MaintWorld 3-4/2022

## 7.4 3.4 Distributed scheduling and optimisation for WM operations

### 7.4.1 Problem description

In confined operational environments such as container terminals, mines, warehouses, construction sites, and airports, managing the horizontal transportation of goods and materials is crucial for maintaining safe, efficient, and cost-effective operations. These settings typically use heavy machinery like straddle carriers, trucks, and automated guided vehicles (AGVs) to transport items between points. The dense and dynamic nature of these environments presents complex pathfinding challenges, known as Multi-Agent Pathfinding (MAPF) problems, where multiple machines must navigate tightly constrained spaces without interfering with one another.

The extension of MAPF into Multi-Agent Pickup and Delivery (MAPD) introduces additional complexity, as agents must now not only find optimal pathfinding but also manage the logistics of loading and unloading goods at specific locations. This task is further complicated by the need for real-time coordination among agents to handle dynamic changes such as newly assigned tasks or sudden changes in the environment, like temporary obstacles or bottlenecks. These challenges often exceed the capabilities of existing pathfinding solutions, which may not adapt well to the highly variable conditions of work machines (WMs).

### 7.4.2 Approach and solution

Our approach leverages distributed algorithm for multi-agent pathfinding (MAPF), integrating both static and dynamic elements of the environment. It utilizes a combination of technologies and methodologies, including network graphs for pathfinding, priority queues for event management, and concurrent processing to handle simultaneous operations among agents. We consider the horizontal transportation problem in maritime container terminals as seen in figure 1.

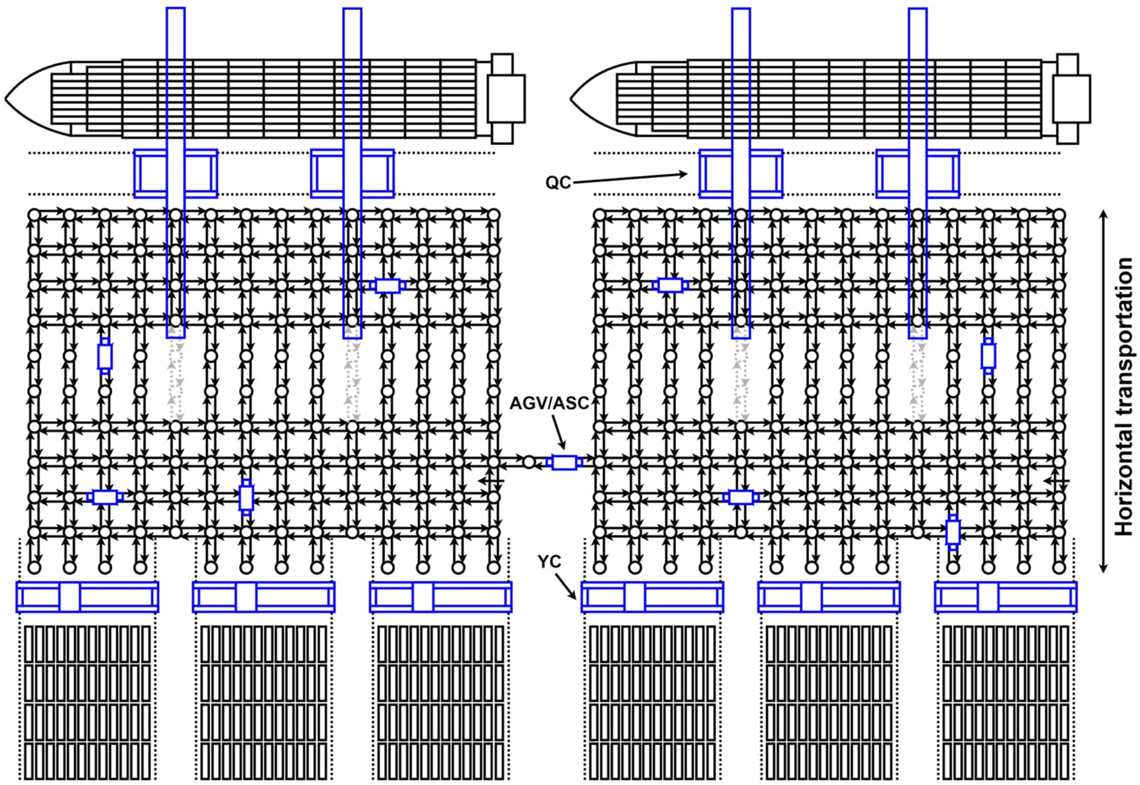



**Figure 1. Horizontal transportation in maritime container terminal**

For machines to be able to independently complete their tasks, the optimization must take this into account. The MAPF algorithm is implemented in a decomposable form such that each machine only needs information about the paths of other machines in each iteration, its own location and destination, and the time-space representation of the map updated in each round. This weighted graph guides machines to avoid collisions via manipulation of the graph edge weights. The approach is based on augmented Lagrangian decomposition which integrates collision avoidance directly into the objective function. This approach allows each agent to operate independently by solving its own decomposed optimization problem while still coordinating with other agents through inter-agent communication to manage conflicts dynamically. The algorithm iteratively adjusts paths based on potential collisions and previously used routes, enhancing overall efficiency and adaptability in dynamic environments such as container terminals.

Messages are transmitted to other machines via a message broker (Pulsar). This allows seamless addition and removal of machines in the task area. Scalability was tested by creating an event queue-based simulator where events occurring on the field produce or publish messages to the message broker's appropriate topics, which interested machines subscribe to according to their needs. In the horizontal transportation example, each quay crane (QC) has its own task list, which publishes a message to the task queue topic when the QC starts moving a container from the ship to the shore. All carriers subscribe to this topic. When a new message arrives in the topic, all available machines receive information about the new job and its upcoming location on the map. The machines check the location of other free machines, which they update in their memory from the location topic, and each calculates which free machine has the shortest distance to the given task. Only the closest machine determines a new destination for itself at the lifting location. This heuristic replaces the high-level optimization in this example. In future research, a distributed task scheduling optimization algortihm should replace this, which combines task allocation and the charging queue optimization of electric work machines based on the attractiveness coefficients produced by EMS. The attractiveness coefficient is determined as a combination of electricity prices and the added value of potential flexibility products according to the research conducted in work package 1.3 of the FEMMA project.

The work phases of the machines change according to the achieved goals. For example, upon reaching the lifting location, the machine sends a status change message to the designated topic, from which other subscribing machines update their memory with the state change of the machine that published the message. Machines must calculate the paths of all machines within the time it takes to move one step. Therefore, the MAPF algorithm used must be computationally fast enough in relation to the machine density of the use case map.

### 7.4.3 Benefits and value

The distributed MAPF algorithm enhances system robustness and scalability by allowing each agent to independently compute its path while coordinating with others, making it well-suited for large-scale and complex environments. By integrating real-time collision avoidance and path adjustments, the algorithm improves operational efficiency and reduces the likelihood of delays in dynamic settings like container terminals. Additionally, its adaptability to changing conditions aligns with the objectives of Industry 4.0, supporting innovations in smart logistics and autonomous operations. The receding horizon principle provides a advantage by enabling continuous recalibration of MAPF strategies in response to unexpected events, such as a tire slip that could derail a machine's adherence to its original planned path.

The incorporation of a simulator and the use of Apache Pulsar for message brokering significantly elevate the practical application of the distributed MAPF algorithm. The simulator allows for detailed scenario testing and optimization before deployment in real-world environments, ensuring that the algorithm performs efficiently under various operational conditions. Apache Pulsar facilitates robust inter-agent communication, enabling real-time data exchange and synchronization across multiple machines, which is critical for maintaining system integrity and responsiveness.

### 7.4.4 Publications

1. Heikkilä, R., Distributed Multi-Agent Pathfinding in Horizontal Transportation, Master's Thesis, Master's Programme in Automation Engineering, Faculty of Engineering and Natural Sciences, Tampere University, May 2023. Available: https://urn.fi/URN:NBN:fi:tuni-202304264607.

# 8 Theme 4: Systemic change over value chain

This theme focused on how systemic change takes place in business environments through further penetration of electrification in WMs. The target was to develop methods and concepts to support industries and companies' transformation towards sustainable business. Sustainable business models and archetypes were identified that guide companies in exploring new opportunities and reconfiguring existing models, emphasizing the importance of diversification to reduce reliance on fossil fuels and enhance financial stability. The application of System-Theoretic Process Analysis (STPA) was highlighted as a valuable tool for identifying safety risks in automated mining operations, contributing significantly to safe system design and evaluation. Additionally, the Task-Technology Fit (TTF) theory was found to be crucial for optimizing digital technology use, ensuring that technological investments align with business tasks to maximize value creation and operational efficiency. There were three tasks which are summarized shortly below:

Task 4.1. addressed the identification of sustainable business models and archetypes that can guide companies in either exploring new opportunities or reconfiguring their existing business models. These archetypes provide a comprehensive understanding of the electrification ecosystem, enabling companies to anticipate and respond to market actions more effectively. Product-Service business models, which bundle products and services, create strong synergies that enhance customer loyalty and provide competitive advantages. Regular assessment and reconfiguration of portfolios are essential to balance innovation with the effective use of existing resources. Furthermore, API and data-driven business models foster the creation of ecosystems that deliver both financial gains and valuable market insights. Diversifying business models not only reduces dependency on fossil fuels but also mitigates risks associated with market volatility and regulatory changes, contributing to greater financial stability and resilience.

Task 4.2 focused on the application of System-Theoretic Process Analysis (STPA) in identifying safety risks in automated mining operations. STPA offers a unique perspective by viewing safety as a control problem and considering the broader system context. The insights gained from the hierarchical control structure and the list of Unsafe Control Actions (UCAs) are crucial for developing loss scenarios and should not be underestimated. While STPA's results are not of a technical nature, they significantly contribute to designing and evaluating safe work environments. The methodology has proven valuable not only in conceptual design phases but also in assessing planned system modifications and reassessing existing systems. The positive experiences with STPA underline its relevance as a complementary tool to other safety analysis methods, and the industry is encouraged to adopt this methodology for systematic and manageable safety analysis.

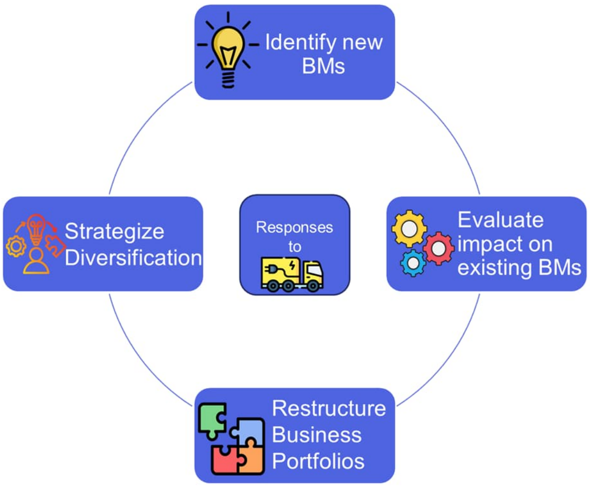
Task 4.3 explored the Task-Technology Fit (TTF) theory, which provides managers with critical insights for optimizing the use of digital technologies, such as big data analytics, to drive business value. TTF emphasizes the importance of aligning technology with specific business tasks to maximize its effectiveness. This alignment ensures that technological investments are used efficiently, addressing complex business challenges and enhancing value creation. By encouraging the strategic restructuring of tasks to better leverage digital tools, TTF helps avoid scenarios where technology is either underutilized or overextended, thereby optimizing the overall performance and contribution of technological applications to business goals.

## 8.1 Challenge description

Achieving carbon neutrality makes electrification crucial for reaching net-zero emissions. Geopolitical shifts and diverse stakeholder demands are pushing equipment manufacturers to explore electrification opportunities for mobile working machines. This shift requires renewing existing business models or adding new, often conflicting, ones to their portfolios.

Managing a portfolio of diverse business models can enhance performance and address sustainability challenges, but it also demands significant financial investment. This is particularly important as companies often need to reallocate resources to support emerging business models. If not carefully configured, they may inadvertently shift organizational goals and even cannibalize the core business.

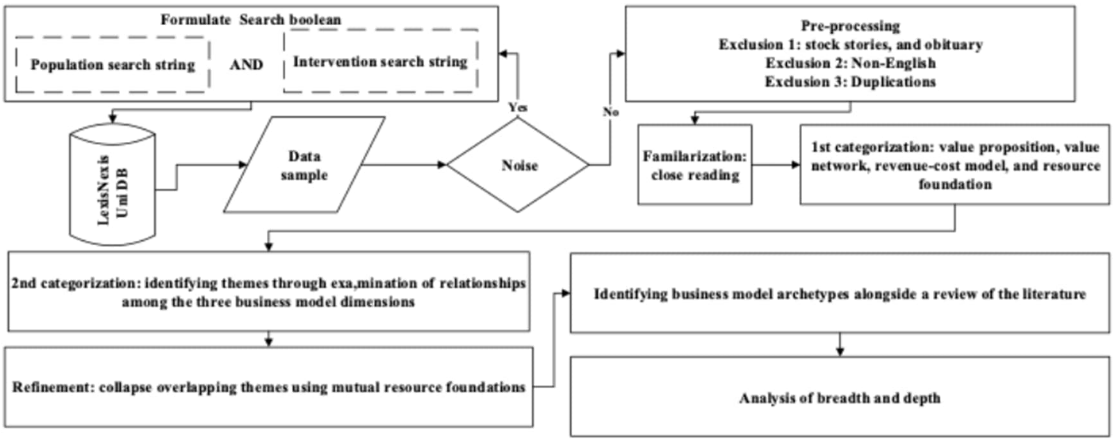
Hence, staying competitive depends on a firm's ability to:




## 8.1.1 Three approaches

*1. Content Analysis of Emerging Business Models in the Mining Industry*

A thematic content analysis on 684 news articles from the LexisNexis database to identify and categorize emerging business models centered on sustainability and electrification within the mining sector.




*2. Two longitudinal case studies of Business Model diversification*

**Sany Heavy Industry:** a longitudinal case study spanning 35 years to examine how Sany Heavy Industry diversified its business models. The study also explored potential conflicts and complementarities between and within business models from a demand-based perspective.

**Epiroc:** Explored business model diversification in Epiroc, focusing on product-service systems and emphasizing the evolution of these models in response to shifting market demands and technological advancements. The study analyzed the synergies and complementarities within the portfolio from a demand-based perspective.

*3. Thematic analysis of API-Driven Transformation*

Explored API-driven business models in Amadeus, using thematic analysis of gray literature to uncover both monetary and non-monetary values generated by managing open and closed business models.

### 8.1.2 Benefits and value

- Identified sustainable business models and archetypes can guide companies to sense opportunities for exploration or to redesign and reconfigure their existing BMs for exploitation.
- These archetypes offer a broader understanding of the electrification ecosystem, enabling companies to better anticipate and respond to the actions of other players in the market.
- Product-Service business models create strong synergies, allowing companies to offer bundled products and services that enhance customer onboarding and loyalty, and create barriers to imitation.
- Regular assessment and reconfiguration of portfolios help balance the exploration of new opportunities with the exploitation of existing strengths.
- API and data-driven business models facilitate the creation of ecosystems and provide companies with both monetary and non-monetary values, such as comprehensive market information.
- Diversifying business models can reduce dependency on fossil fuels revenue streams, mitigating risks associated with market volatility and upcoming regulatory requirements. By spreading risk across different models, companies can achieve greater financial stability and resilience.

### 8.1.3 Publications

1. Heshmatisafa, Saied; Seppänen, Marko (2024), Exploring emerging business models for electrified machinery, Digital Transformation and Innovation Management (DTIM2024) Budapest, Hungary. *Outstanding paper award.*
2. Heshmatisafa, Saied; Seppänen, Marko (2024), Exploring the dynamics of business model portfolio: Unveiling strategic restructuring (Case Sany), PICMET 2024 Portland International Conference on Management of Engineering & Technology. USA.
3. Heshmatisafa, Saeid; Seppänen, Marko (2023), Business model diversification through Product-Service Systems: Demand-relatedness perspective, XXXIV ISPIM Innovation Conference, held in Ljubljana, Slovenia.
4. Heshmatisafa, Saeid; Seppänen, Marko (2023), Exploring API-driven business models: Lessons learned from Amadeus's digital transformation, Digital Business, https://doi.org/10.1016/j.digbus.2023.10,,2023
5. Heshmatisafa, S., & Seppänen, M. (2023). Exploring Business Models of Electric Mobile Work Machines in the Age of Decarbonization. In *Business Model Conference*.
6. Heshmatisafa, S., Huhtamäki, J., & Seppänen, M. (2022). Visualizing the maturing global API ecosystem. https://scholarspace.manoa.hawaii.edu/bitstreams/72ab5c3d-9a1b-484b-95ac-52cc72212bf3/download

## 8.2 System-theoretic approach for the identification of autonomy and electrification related risks

Challenge description

Autonomous mining reshapes contemporary mining practices as it plays an increasing role in bringing value to customers. The benefits encompass improvements in operational efficiency, safety, and process reliability while offering flexible maintenance programs that reduce downtime and costs. The shift towards increased machine autonomy will significantly impact the nature of work tasks and roles at mining sites. For example, manual drivers will cooperate with automated or autonomous WM at the site, or transition to roles as remote operators or system operators located in control rooms. The growing complexity and functionality of these systems introduce new risks, necessitating a comprehensive safety analysis.

Despite being well established in industry, traditional hazard analysis methods (Preliminary Hazard Analysis (PHA), fault tree analysis (FTA), failure modes and effects criticality analysis (FMECA), event tree analysis (ETA), and hazard and operability analysis (HAZOP)) fall short in adequately identifying risks associated with complex systems. These methods typically involve examining system components separately and in isolation, concentrating on identifying failures, faults, and their effects on single system level. However, in complex systems, such as mine automation systems, losses may not only occur due to component failures but rather because of unpredictable and undesired interactions among system elements. Rooted in systems-theory, Systems-Theoretic Process Analysis (STPA) can address this complex, non-linear way of how losses can arise.

STPA, published in 2018 at MIT in a 200-pages detailed STPA Handbook is rather new to the industry and foremost used at research institutes. We believe that current and future STPA practitioners will appreciate clear, concise, and straightforward STPA instructions. Therefore, we conducted a STPA study and based on these learnings produced an effective and concise alternative, the “STPA Guide”.

### 8.2.1 Approach and solution

Our guide leads through the STPA step by step and introduces best practices from literature and personal experiences, highlighting deviations to complement the Handbook effectively. While it especially addresses safety engineers with their efforts to design and assess complex, socio-technical systems everyone interested in learning how to conduct STPA will benefit. In essence, the guide serves as a valuable companion to enhance the understanding and application of STPA.

The Systems-Theoretic Accident Model and Processes (STAMP) forms the underlaying model for STPA and includes non-linear relationships of technical and organizational structures, design and requirements flaws, as well as dysfunctional interactions between components that themselves act as intended. The systems theory, the base of STAMP and STPA, goes beyond the assumption that unwanted scenarios are a result of a simple chain of directly related failure events or component failures. Instead, it treats a system with its complex processes and interactions among other system components as a whole, and not as sum of its parts. A system has dynamic properties in which system elements engage and impact each other. When these components interact new, non-obvious ways of how accidents can emerge arise.

Consider the example of an autonomous vehicle operating in an isolated area at 30 km/h. Although the system designers perceive this speed as safe due to human segregation from the operational environment, inclement weather conditions can transform the roads into slippery surfaces, lengthening the braking path and potentially causing accidents if the speed is not adjusted. These accidents occur without any actual machinery components failing, highlighting the inadequacy of examining system components separately and in isolation, a common practice in many traditional hazard analysis methods.

We applied STPA to gain practical experience, and evaluate the applicability of STPA for automated mining operations. Therefore, we assessed the operation of automated and remotely operated drill rigs in a mining pit when a human is nearby. The analysis explores a use-case regarding a typical daily maintenance task. In this scenario, the mode of operation must be adjusted upon the maintenance person’s approach to and return from a drill rig. The system under investigation includes three automated drill rigs and a teleoperation station. Additionally, the study explores the potential of STPA for identifying system constraints, requirements, and safety goals in the context of mine automation systems.

The method is implemented in four stages: defining the analysis’ purpose, modelling the control structure, identifying the unsafe control actions (UCA), and finally describing loss scenarios (Figure 1).

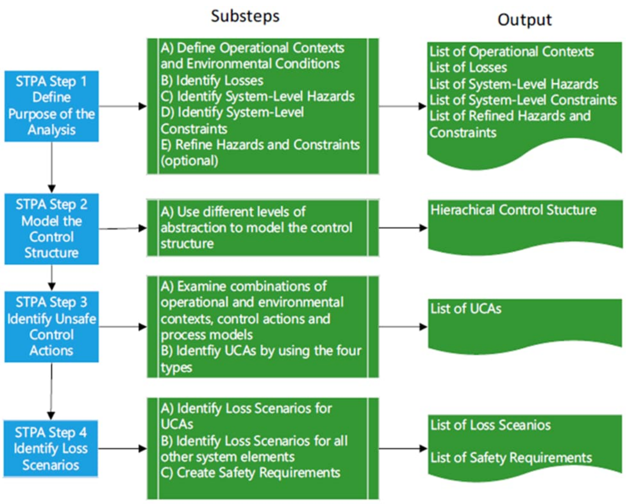



Figure 1. STPA procedure and output.

The first step involves defining the purpose of the analysis, which is guided by sub-steps that include specifying losses, system-level hazards, and system-level constraints. In instances where a more detailed perspective is deemed beneficial, hazards and constraints may be optionally refined. Losses play a crucial role in steering the analysis, as they guide the focus of the STPA practitioner on specific hazards to investigate. In the context of STPA, hazards refer to the states a system can be in just before a loss might occur.

The second step, the modelling of the control structure, lays the groundwork for the actual hazard analysis. The control structure, serves as a hierarchical representation of the system elements related to system control, encompassing components such as (human) controllers, sensors, and actuators. Commands, also called as control actions (CAs), are represented by downward arrows, and are transmitted from elements with higher hierarchical power to those with less. Feedback streams, represented by upward arrows, convey information to support controller decision-making. External inputs are depicted through horizontal arrows and must be included if their neglect otherwise leads to an incomplete representation of the system under investigation.

STPA gives special attention to CAs by dedicating Step 3 to identifying of how assumingly suitable and safe CAs can become unsafe. This step results in a list of UCAs, describing conditions that could lead to their realization. The analysis distinguishes between four types of UCAs: "Provided," "Not provided," "Provided, but at the wrong time" (too early, too late, or in the wrong order), and "Provided for an inappropriate duration" (for too long or too short).

Objective of STPA Step 4 is to examine all system elements like physical components, feedback, other inputs, and controllers for their potential to trigger UCAs, and give rise to losses. Moreover, since STPA Step 3, identifies UCAs without exploring how they translate into losses, Step 4 bridges this gap by examining the mechanisms through which also UCAs can manifest as actual losses. The result of this step, and the analysis as a whole, is a collection of textual descriptions referred to as loss scenarios. Essentially, these loss scenarios describe causal relationships among contributing factors, that can lead to the realization of one or more losses from step 1.

### 8.2.2 Benefits and value

We learned that not only the official output of the STPA process – the collection of loss scenarios – yields insights to possible safety risks within the system under investigation. Also, the results from steps 2 and 3—the hierarchical control structure and the list of UCAs—, which support the creation of loss scenarios, provide crucial information which shall not be underestimated. We see STPA as a relevant complementation to other safety analysis tools as it leads to noteworthy findings that support the design and evaluation of automated mining operations. STPA gives valuable insights as it views safety as a control problem and considers effects within and to the whole system process. While STPA results are not of technical nature, they can aid in creating a safe work environment and understanding factors affecting the work at site. STPA proved to deliver valuable input for discussions during system’s conceptual design phase. Additionally, the tool appears to contribute to assessing planed system design modifications as well as reassessing already existing systems.

Due to these positive experiences with STPA we recommend the industry to learn how to use the methodology and apply it. We hope that the STPA Guide enables new practitioners from the industry to systematically analyze systems without becoming overwhelmed by their complexity. STPA allows to break down the analysis into manageable steps, providing the opportunity to scrutinize each CA and feedback individually, giving each the attention it deserves. Learning STPA independently is feasible, but this guide aims to make the learning journey more effective.

### 8.2.3 Publications

1. Berger, J. (2024). STPA Guide. VTT Technical Research Centre of Finland. VTT Research Report No. VTT-R-00848-23. https://cris.vtt.fi/en/publications/stpa-guide
2. Berger, J. Tiusanen, R. (2024). Confidential VTT Project Report: FEMMa, Task 4.2 - Sandvik case, STPA report
3. Berger, J. Tiusanen, R. Malm, T. (2024) Safety of Industrial Automated Systems - SIAS 2024. Conference presentation. https://cris.vtt.fi/en/activities/assessing-an-automated-mining-operation-with-stpa

## 8.3 From Fit to Value: Insights on Business Analytics and Digital Transformation

Challenge description

The application of business analytics (BA) to address business problems and seize opportunities has led to significant improvements in firm performance, affirming the relevance and suitability of BA in meeting business needs through effective task execution. Building on this, it was investigated how value capture through data analytics is influenced by domain knowledge within the specific context in which data analytics is applied, particularly in data-infused business models (such as big data analytics). These models underscore that while all businesses utilize some form of data analytics, the extent and effectiveness of its application vary, making domain knowledge a critical factor in optimizing the impact of data analytics on business performance.

### 8.3.1 Approach and solution

The problem of task-technology fit (TTF) was addressed from two different perspectives, each contributing unique insights into the interaction between technology and tasks, particularly in the context of business analytics and big data analytics (BDA).

First, TTF was approached by examining the extent to which business analytics can address business problems, focusing on the iterative application of business analytics to enhance problem understanding and solutions. It adopts a qualitative approach using pattern matching to compare theoretical propositions with empirical data from interviews. This study emphasizes the dynamic nature of fit, arguing that both under-fit and over-fit can be acceptable depending on the costs of achieving an ideal fit and the potential unaffected outcomes. The study highlights the distinction between creating and applying business analytics solutions, suggesting that these roles may have different implications for TTF. Ultimately, this research enriches the literature by linking the effectiveness of business analytics to business value through problem resolution, providing a practical view of how TTF operates in a business context.

Second, big data analytics (BDA) and its role in generating business value was approached, proposing a novel approach to understanding TTF. This study argues that traditional TTF approaches, which focus on how technology meets task requirements, may not fully capture the dynamic and malleable nature of digital technologies like BDA. It introduces a 2 × 2 matrix framework that accounts for the reconfigurability of tasks and the editability of BDA, suggesting that tasks can be structured to fit the functionality of technology, not just the other way around. This approach provides new insights into how the interaction between tasks and BDA can evolve over time, offering a more flexible and adaptive understanding of TTF in the context of digital technologies.

Together, these studies offer complementary perspectives on TTF. The first emphasizes the practical application of business analytics and its iterative nature in achieving fit, while the second proposes a theoretical framework that accounts for the unique characteristics of BDA, suggesting a more reciprocal relationship between tasks and technology. Both studies contribute to a deeper understanding of how TTF theory can be applied to modern, dynamic technologies, ultimately enhancing the ability of organizations to generate business value from their technological investments.

### 8.3.2 Benefits and value

The Task-Technology Fit (TTF) theory offers valuable insights for managers seeking to optimize the use of digital technologies like big data analytics (BDA) to drive business value. By highlighting that business value arises from the alignment between technology and tasks, TTF guides managers to ensure that their technological applications are well-matched to specific business needs. It also encourages the strategic restructuring of tasks to better utilize the capabilities of digital tools. Understanding the limits of both technology and task reconfiguration helps avoid under-fit or over-fit scenarios, enabling more effective and efficient use of technological investments to solve complex business problems and enhance value creation.

### 8.3.3 Publications

1. Muchenje, G. (2024). Determinants of business value realisation from the use of business analytics - The role of fit, complementarity and causal ambiguity. Dissertation.
2. Muchenje, G., Seppänen, M., & Li, H. (2024). Problem resolution with business analytics: a task-technology fit perspective. *Internet Research*, *34*(7), 118-138. https://doi.org/10.1108/INTR-07-2023-0527
3. Muchenje, G., & Seppänen, M. (2024). Reflecting on the imprecision of digital transformation. In *2024 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*
4. Muchenje, G., & Seppänen, M. (2023). Unpacking task-technology fit to explore the business value of big data analytics. *International Journal of Information Management*, *69*, 102619. https://doi.org/10.1016/j.ijinfomgt.2022.102619
5. Muchenje, G., & Seppänen, M. (2023, June). Temporality foundations impacting the speed of change in digital transformation. In *2023 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1-6). IEEE.
6. Sorri, K., Mustafee, N., & Seppänen, M. (2022). Revisiting IoT definitions: A framework towards comprehensive use. *Technological Forecasting and Social Change*, *179*, 121623. https://doi.org/10.1016/j.techfore.2022.121623