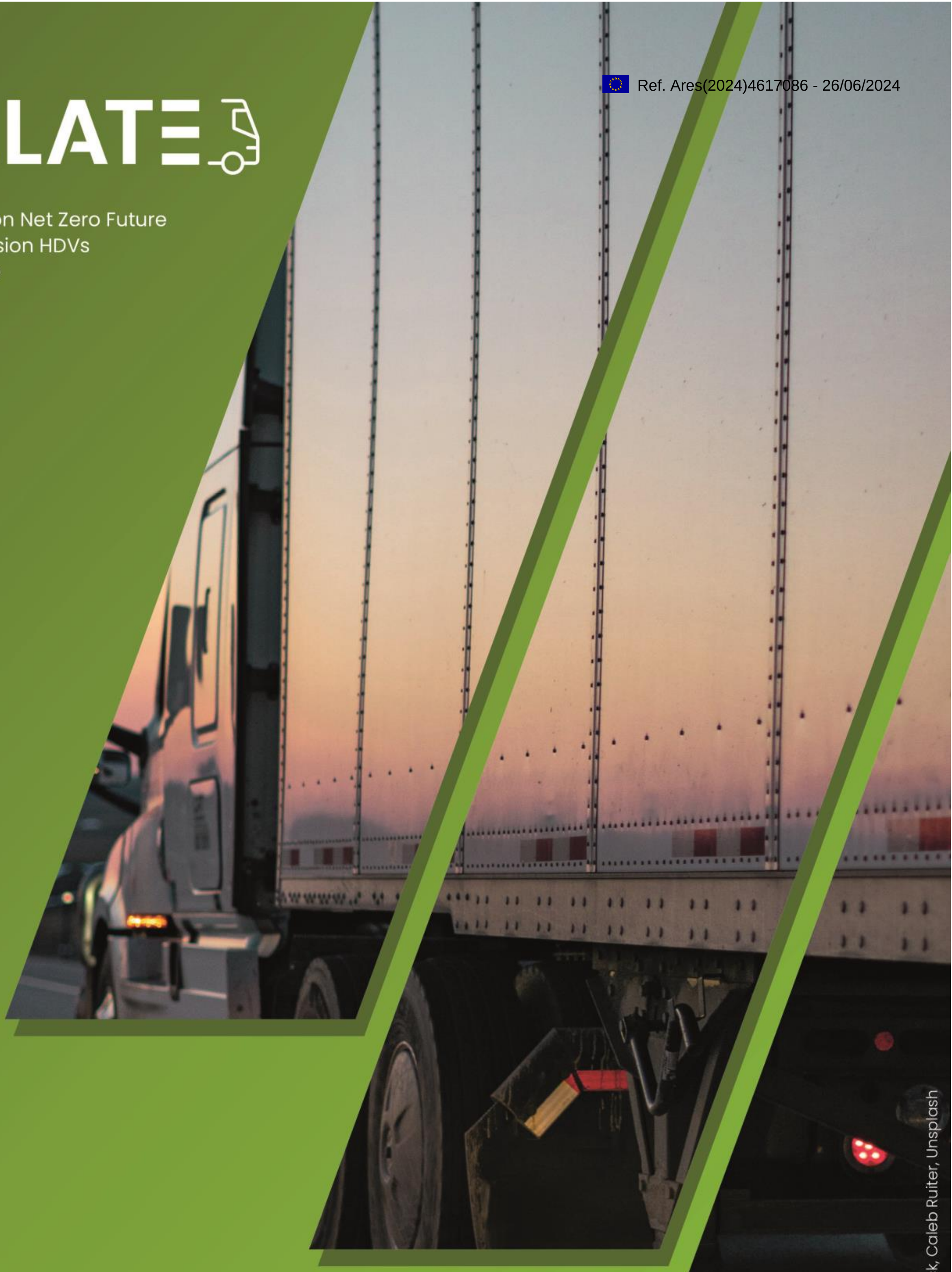
ESCALATE

Powering European Union Net Zero Future
by Escalating Zero Emission HDVs
and Logistic Intelligence



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Definition of digital twin requirements and architectures

Project deliverable D5.1

R. ÅMAN (VTT)

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Project Executive Summary

ESCALATE, an EU funded Research and Innovation project, has been awarded funding under the HORIZON-CL5-2022-D5-01 call, highlighting its significance within the academic and scientific community. The primary objective of ESCALATE is to showcase and demonstrate the efficacy of high-efficiency zero-emission heavy-duty vehicle (z-HDV) powertrains, with a targeted increase of up to 10% in their overall efficiency. Specifically tailored for long-haul applications, these powertrains are designed to provide an impressive range of 750+ kilometres without the need for refuelling or recharging, while simultaneously ensuring consistent performance during daily operations over a period of six months or more under real-world conditions. To achieve these ambitious goals, ESCALATE focuses on the development of meticulously designed modular building blocks, which are intended to attain a Technology Readiness Level of 7 or 8. These modular components will serve as the foundation for three distinct types of z-HDVs, namely battery-HDV (b-HDV), fuel-cell-HDV (f-HDV), and range extender-HDV (r-HDV). The utilization of innovative business model innovations will be instrumental in optimizing the integration and utilization of these standardized and modular building blocks, further enhancing their efficiency and effectiveness. Moreover, the ESCALATE project aims to contribute valuable insights to the scientific community through the production of three comprehensive white papers. These papers will delve into various aspects of z-HDV technology, with one white paper focusing on defining a clear pathway to reduce well-to-wheel greenhouse gas emissions specifically from heavy-duty vehicles. The formulation of this pathway will be informed by rigorous analysis, utilizing both empirical results and policy assessments, thereby establishing a robust foundation for future efforts in reducing the environmental impact of HDVs. Through its multifaceted approach, ESCALATE strives to advance the knowledge and understanding of high-efficiency z-HDV powertrains, foster technological innovation, and contribute to the ongoing efforts of EU aimed at achieving sustainable and environmentally friendly transportation systems.

ESCALATE partners

List of participating countries:

- Belgium
- Denmark
- Germany
- Spain
- Estonia
- France
- Finland
- Greece
- Poland
- Portugal
- Austria
- Turkey
- UK

List of partners:

- FEV Europe Gmbh & FEV France (FEV) - Project coordinator
- University Of Surrey (USR) - Technical coordinator
- Mercedes-Benz Turk As (MBT)
- Brussels Research And Innovation Center For Green Technologies (BRING)
- Teknologian Tutkimuskeskus VTT Oy (VTT)
- Virtual Vehicle Research Gmbh (VIV)
- Aristotelio Panepistimio Thessalonikis (AUTH)
- Polis - Promotion Of Operational Links With Integrated Services, Association Internationale (POLIS)
- Inegi - Instituto De Ciencia E Inovacao Em Engenharia Mecanica E Engenharia Industrial (INEGI)
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
- Rheinisch-Westfaelische Technische Hochschule Aachen (RWTH)
- Bmc Otomotiv Sanayi Ve Ticaret Anonim Sirketi (BMC)
- Engie Energie Services (ENGIE)
- Commissariat A L Energie Atomique Et Aux Energies Alternatives (CEA)
- Fev Tr Otomotiv Ve Enerji Arastirmave Muhendislik Limited Sirketi (FEV TR)
- Ai4sec Ou (AI4SEC)
- Ballard Power Systems Europe As (BLRD)
- Kempower Oy (KEM)
- Hydrogen Europe (HEU)
- Ergtech Spolka Z Ograniczona Odpowiedzialnoscia (ERG)
- Pbx Gmbh (PBX)
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- Bsa Inno & Tech Gmbh (BSA)
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- Valmet Automotive EV Power Oy (VAL)
- Ortem Elektronik As (ORTEM)
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Deliverable executive summary

ESCALATE's primary focus is on the development of a modular and scalable vehicle platform for heavy-duty long-haul applications. The platform incorporates innovative powertrain architecture based on central electric machine (EM) or electric axle (e-axle) with modularity concepts. The integration of central EM and e-axle solutions ensures a comprehensive approach to electric and control architecture.

Simulation and digital twins are utilized in the project to reach and ensure the performance of the vehicles and powertrains. The same simulation approach is utilized in a digital twin environment to be used during vehicle operation. Using the digital twin system and the AI application the vehicle operation is reaching high energy efficiency on vehicle and fleet level and reliable operation using predictive maintenance functions.

This document describes the specifications and requirements for the trustworthy Modular Digital Twins of demonstrator vehicles cost-effective standardized modular and scalable electric powertrain components for heavy-duty long-haul applications. Task 5.1 includes definition of requirements and specifications of computational platform for all use cases. This includes the computational platform architecture, simulation model methodology, and tool chain selection as well as data management.

With the combination of AI-based techniques, the digital twins will be utilized for efficient operation, predictive maintenance, fleet management and explainable models. Furthermore, the Trustworthy Modular Digital Twins of the demonstrator vehicles will be used for early identification and assessment of “Innovations True Value” (impact assessment and valuation) in the context of 2Zero targets, continuous optimization of vehicle systems and their life-cycle assessment (LCA).

By defining the requirements and specifications, this deliverable sets the stage for the development of a cutting-edge electric powertrain system that meets the demands of cost-effectiveness, modularity, scalability, and performance. In this context, specific requirements are outlined for fuel cell (FC), hydrogen (H_2) storage, battery pack (BP), electric motor (EM), power electronic controller (PEC), DC/DC converter, Eddy current brake and cooling system components.

Overall, this deliverable provides a roadmap for the development of beyond-the-state-of-the-art, standardized, modular electric powertrain systems, showcasing ESCALATE's commitment to driving advancements in the field of zero emission heavy duty vehicle technology and fostering a more sustainable future for transportation.

Considering each demonstrator use-case being of different structure and intended for different work cycles, it, naturally, creates a great variety in the complexity and diversity of requirements for the digital tools, methods and deployment of Digital Twins (DT). Thus, it is recommended that the requirements and definitions for the DTs will be updated over the lifetime of the project whenever needed.

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List of abbreviations and acronyms

ACRONYM	MEANING
AI	Artificial Intelligence
API	Application Programming Interface
AC / DC	Alternating Current / Direct Current
BOL / EOL	Begin / End of Life
CAN	Computer-Area Network
CE, ECE	Conformité Européenne, United Nations Economic Commission for Europe
CPU, GPU	Central / Graphics Processing Unit
CRYPTaaS	Cryptography-as-a-Sevice
DT	Digital Twin
EM	Electric Motor
ESS	Energy Storage System
FAIR	Findability, Accessibility, Interoperability, and Reusability
FC / FCS / FCEV	Fuel Cell / System / Electric Vehicle
FMI / FMU	Functional Mock-Up Interface / Unit
GNSS, GPS	Global Navigation Satellite System / Positioning System
GPRS	General Packet Radio Service
4G, 4.5G, 5G, LTE	Gen. of broadband cellular network technology, Long-Term Evolution y
HiL / SiL	Hardware- / Software-in-the-Loop
b-HDV	Battery electric Heavy-Duty Vehicle
f-HDV	Fuel cell Heavy Duty Vehicle
r-HDV	Range extended Heavy Duty Vehicle
z-HDV	Zero-emission Heavy Duty Vehicle
HSM	Hardware Security Module

ACRONYM	MEANING
HTTP(S)	Hypertext Transfer Protocol (Secure)
IoT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCA	Life-Cycle Assessment
MQTT	Message Queuing Telemetry Transport
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
OTA	Over the Air
PE	Power Electronics
PTC	Predictive Thermal Control
RAM	Random-Access Memory
REST	Representational State Transfer
SMS	Short Message/Messaging Service
SoC / SoH	State-of-Charge / Health
TCO	Total Cost of Ownership
TLS	Transport Layer Security protocol
UC	Use case
V2C / V2N	Vehicle to Cloud / Network
WiFi	Wireless Fidelity
XAI	Explainable AI

1 Introduction

In WP5 the requirements, specifications, and architectural design for modular and scalable physical models for all UCs are being made by means of DTs. This Deliverable is a definition of available sub-models and computational platforms to start with efficient simulation work. E.g., models from FC, ESS etc. will be collected. Multi-domain tool chains for faster development times of real demonstrators will be chosen to support the hardware testing in WP6 most efficiently. Interfaces in tool chains will be defined with the focus on FAIR, and further, open standards like FMI are intended. The FCHJU project “Virtual-FCS”, can be used to create synergies to the attempted system modelling and AI considerations. (SINTEF , 2022).

Identification of requirements from the operator's point of view will be done. The focus will be on operational efficiency perspective, predictive maintenance, and data management definition. Requirements and design for fleet management and LCA will be defined. The specifications for AI models, data source compiling, definitions, will be created. Requirements will further be defined based on stochastic and machine learning techniques that will link to LCA in WP7 AI-powered toolchain and connectivity requirements.

Considering each demonstrator UC being of different structure and intended for different work cycles it, naturally, creates a great variety in the complexity and diversity of requirements for the digital tools, methods and deployment of DTs. Thus, it is recommended that the requirements and definitions for the DTs will be updated over the lifetime of the project whenever needed.

1.1 Background and Context

In this Deliverable the requirements, specification and architectural design of modular digital twins are discussed by means of the tasks included in WP5 Digital Twin & AI-based Managerial Tools. The activities are carried out by the partners in T5.1 Requirements, Specification and Architectural Design of Modular Digital Twins even though there are plenty of more partners involved in whole WP5 and, thus, it requires the partners of T5.1 to interlink the partners in similar activities.

2 Digital Twins in the Automotive Sector and in ESCALATE

ESCALATE project structure is presented in Figure 1. Requirements of the pilot vehicles and their operation are defined in WP2. These requirements and specifications are the inputs to powertrain dimensioning and design in WP3 and for the needed charging and refuelling infrastructure design in WP4. Digital twins enabling simulation services for the pilots are defined and implemented in WP5. Pilots are located under WP6, which integrates and validates the outcomes of the design phases and demonstrates each pilot in use.

In the implementation of the project, the scope of the Digital Twins in four Pilots (1-4) and the scope of a Digital Model in Pilot 5 is set as the following objectives. The Objectives O5 need to be considered as requirements.

- O5.1: Development of 4 vertically integrated and validated modular DTs of the ESCALATE pilots and their optimal operation in the pilot missions.
- O5.2: Design and development of open multi-domain platform design for ESCALATE DTs with FMIs, enabling exchangeability of various connections.
- O5.3: Two equation-based DT models of novel metal hydride based thermal management.
- O5.4: Valorisation of the effect of innovations quantitatively in 5 pilots through the assessment of "Innovation True Value" in terms of time, cost, efficiency, effectiveness, eco-friendliness, long-term sustainability, and optimization.
- O5.5: Continuous optimisation of adaptive energy management algorithms via DTs for enhanced energy efficiency (up to 10%).
- O5.6: DT integrated and holistic optimization of operational costs for minimized TCO with special focus on variables such as fuel and hydrogen, operation and maintenance, infrastructure availability as well as the future CO2 tax rate.
- O5.7: Prevention and minimization of operational environmental impacts through the combination of LCA and route management tools, integrated into DTs of the 5 ESCALATE demonstrators.
- O5.8: System design optimization for resource efficiency and lower life cycle environmental impacts through LCA studies to achieve climate neutrality as mentioned in 2Zero targets.
- O5.10: Integration of AI-based predictive maintenance tools to ESCALATE DTs for early fault management and enhancement of component life.

The realization of requirements set for DTs in projects will be measured with the following KPIs.

- KPI-28: Four modular DTs of ESCALATE demo vehicles in Pilot 1-4 and a Simulation Demonstrator of vehicle in Pilot 5 will be created.

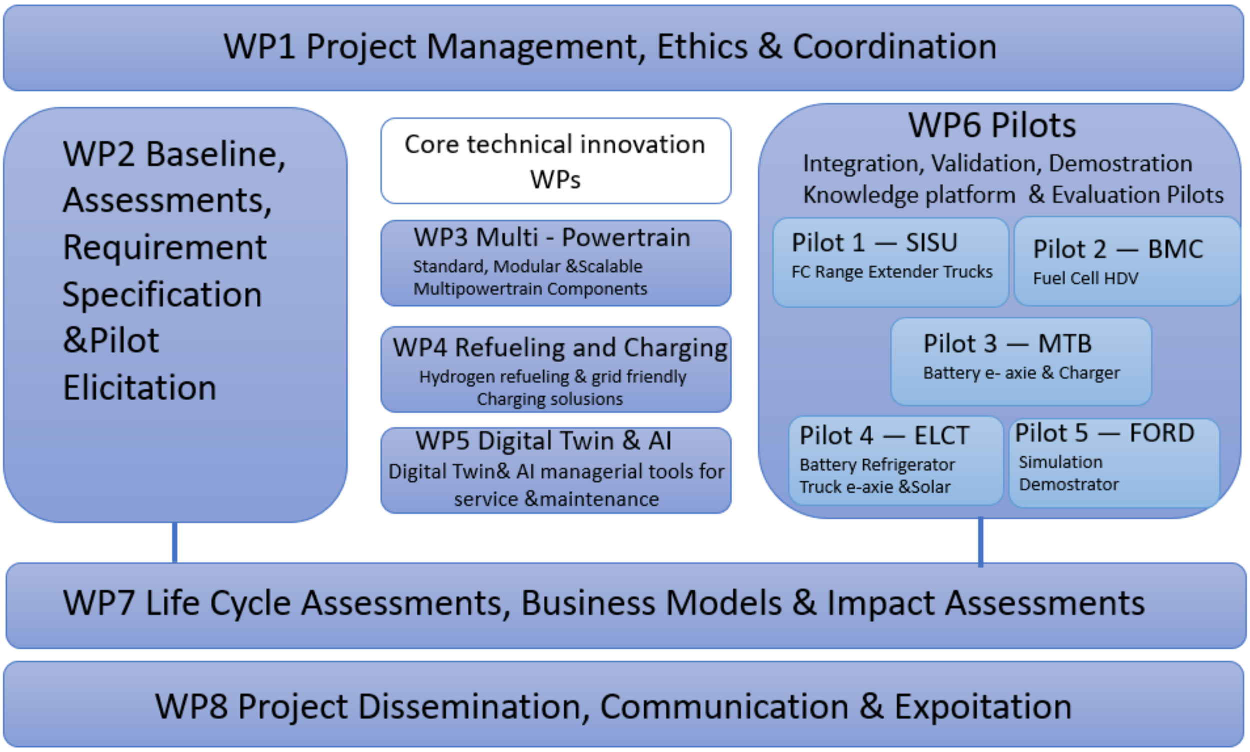


Figure 1. ESCALATE project structure.

2.1 Pilot 1

SISU Pilot 1 is a battery electric truck with a FC range extender (r-HDV) designed for regional and long-haul missions. The pilot is to be tested with GVW of 40 tons, but the three-axle tractor with 6x4 axle configuration is aiming to higher GVWs and the pilot will be scaled also up to 76-ton GVW. The pilot 1 answers to demanding Nordic long-haul operations with high GVWs and energy efficiency and environmentally friendly transport solutions.

The focus of the digital twin for Pilot 1 is on energy management during the operation for energy efficient driving to ensure longer ranges in different real-world weather and road conditions and in various transport tasks. Another important aspect is to lower environmental impact by energy efficient driving and enhancing component lifecycle using AI-based predictive maintenance tools. The digital twin includes powertrain components, electric motor, inverter, battery, and fuel cell, as well as transmission and vehicle models (see Figure 2).

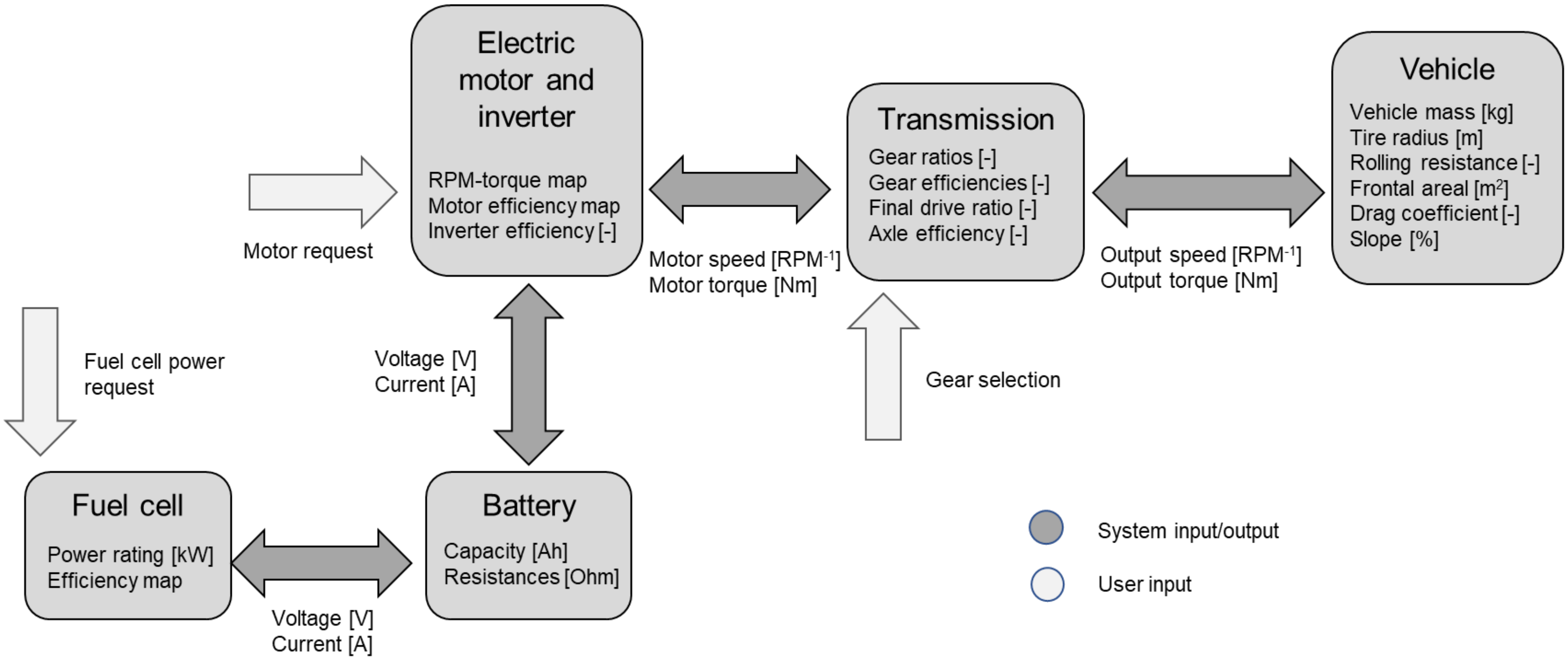


Figure 2. Overview of the digital twin components, their connections and inputs and outputs for Pilot 1.

2.2 Pilot 2

BMC Pilot 2 will be a Hydrogen Fuel Cell Truck. As depicted in Figure 3, there will be two FC units placed serially together in the bottom side of the driving cabin. FC units will be fed from four Hydrogen tanks. This volume has been calculated to reach 800 km range with a single refill, which is one of the pilot's KPI's. The battery will be able to be charged from the FC units. A new generation E zero emission electric motor will drive the f-HDV and the truck will have innovative thermal management systems with other technological features, which have been listed in the project goals.

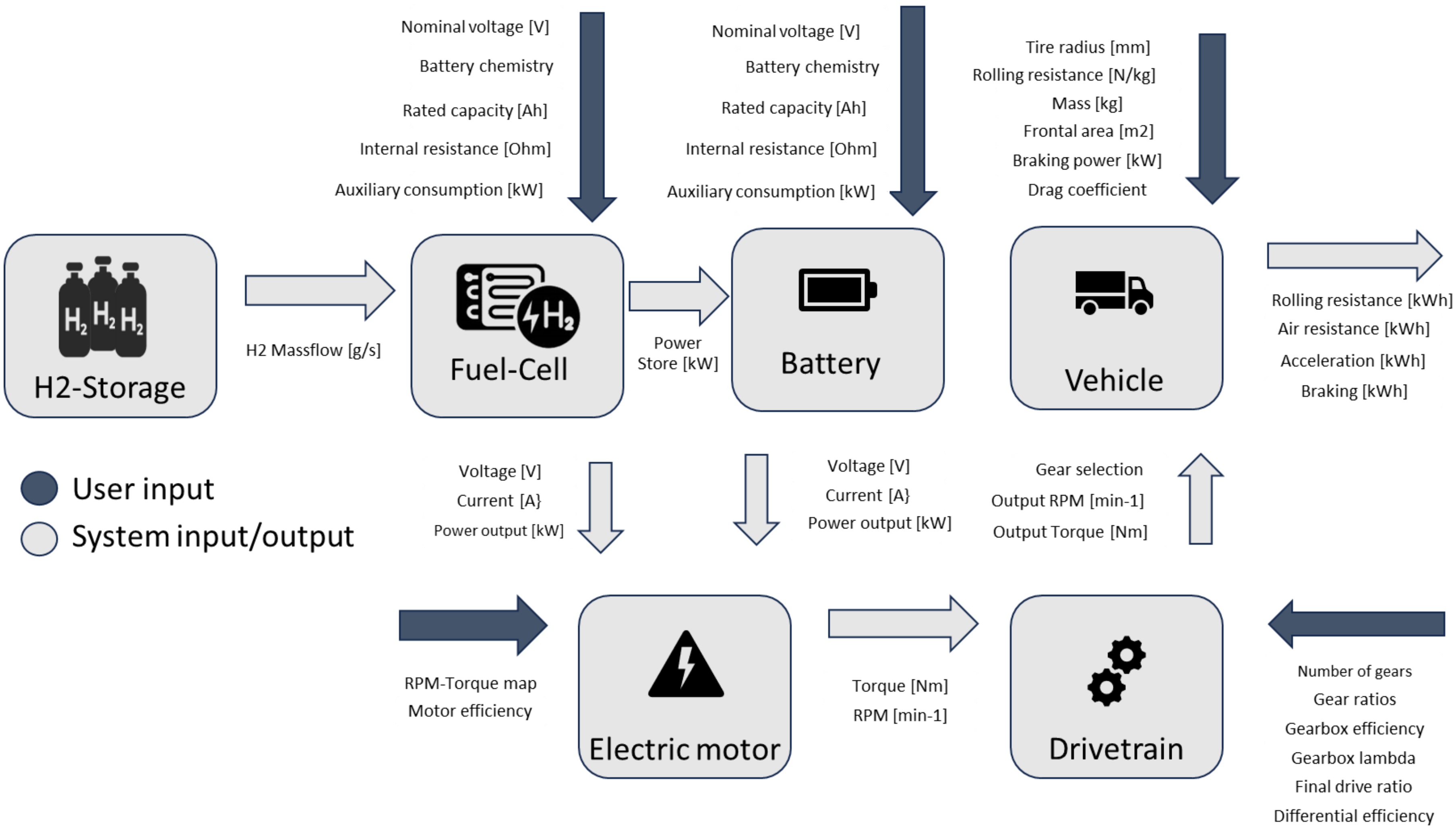
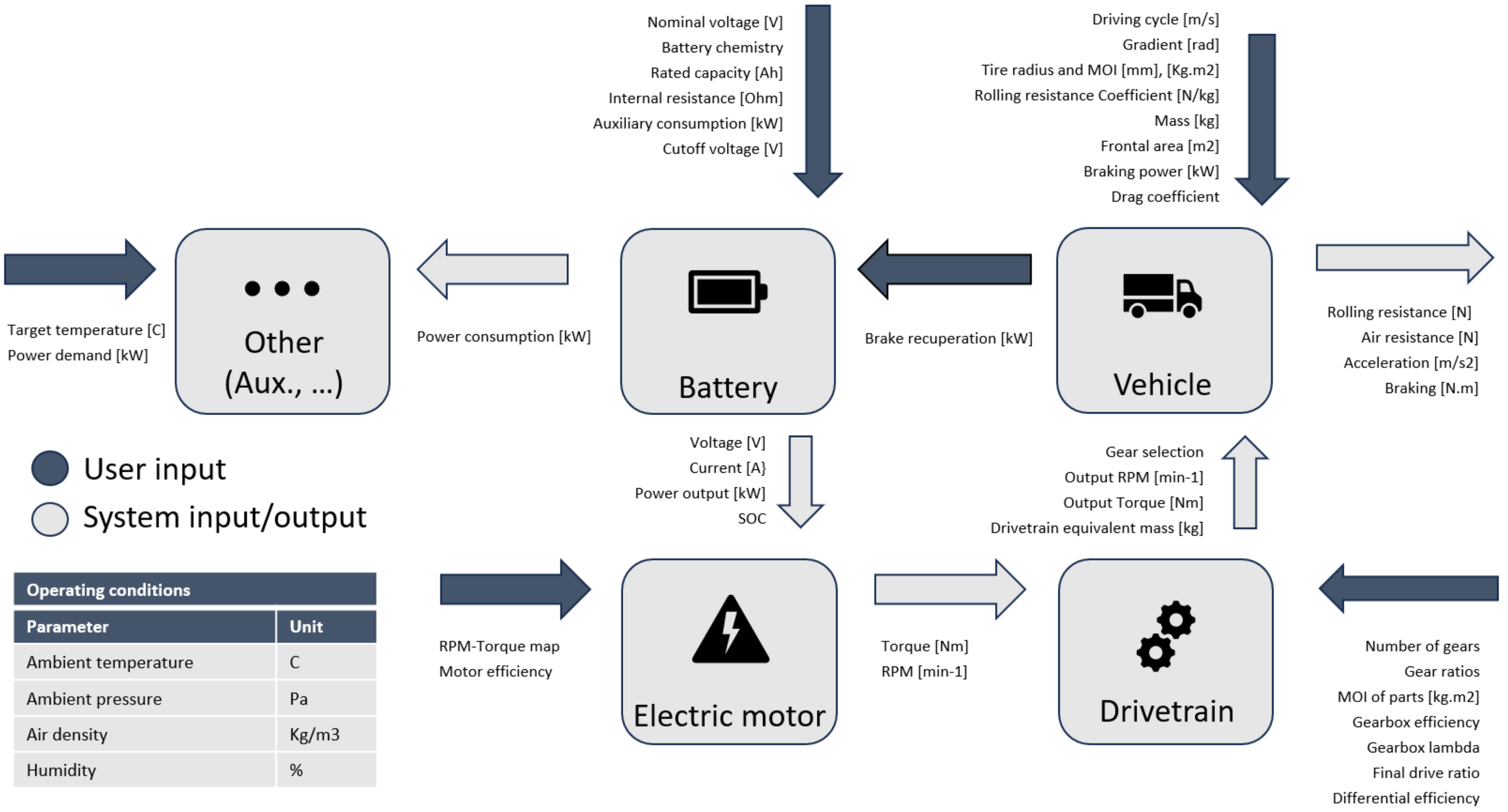


Figure 3. Pilot 2 BMC Powertrain Layout.

2.3 Pilot 3

In Pilot 3 a battery-electric truck for long-haul applications is studied. Figure 4 presents the MBT Powertrain Layout.



Operating conditions	
Parameter	**Unit**
Ambient temperature	C
Ambient pressure	Pa
Air density	Kg/m3
Humidity	%

Figure 4. Pilot 3 MBT Powertrain Layout.

2.4 Pilot 4

The ELECTRA PILOT 4 is a fully electric-driven truck designed for long-haul and local distribution operations. The payload capability is up to 40t with two refrigeration compartments on board. To overcome the technological barriers in terms of range and efficiency roof-mounted photovoltaic solar panels and optimal onboard energy control minimise the power for the refrigeration system. In addition, modular e-axle with wide bandgap inverter technology and fast-charging modular solid-state battery will increase the efficiency of the powertrain and its use of e-driven trucks.

The model is designed to simulate BEV behaviour through targeted driving cycles and to track component health, efficiency, and consumption. The model contains several blocks (Figure 5) to represent vehicle components like the electric traction motor, DC-DC converter, inverter, battery, transmission, tires as well as additional sub-models as - solar panels, fridge compartments, HVAC, additional auxiliaries, and the vehicle body. The model processes the driving cycle through a driver controller to generate driving commands for the vehicle, which are then processed through the ECU to determine vehicle behaviour during the driving cycle. The model accommodates auxiliary component consumption, solar panel, and brake recuperation. With additional predictive maintenance services, the state of health of components are monitored during operation.

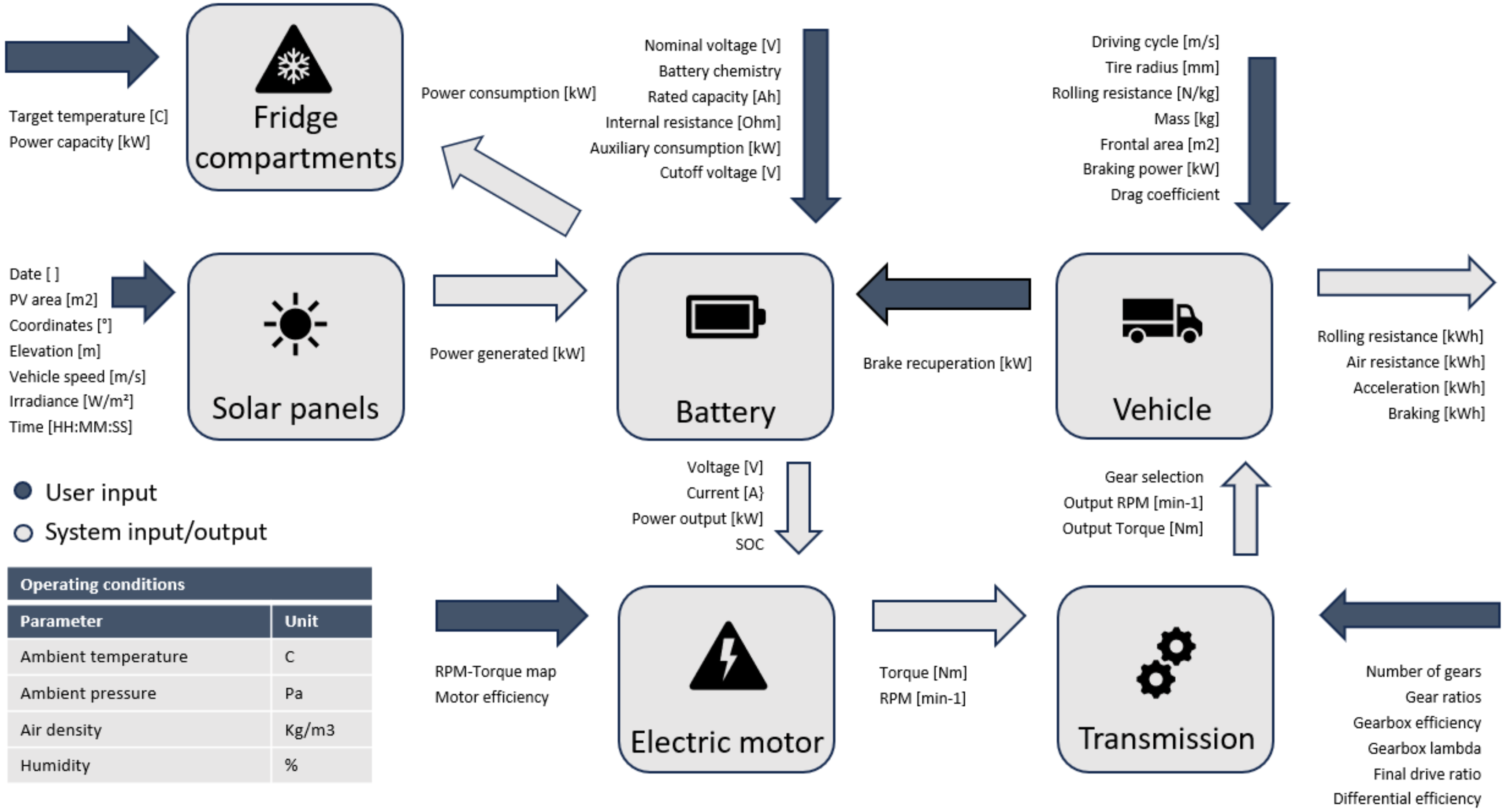


Figure 5. Overview of the digital twin components, their connections and inputs and outputs for Pilot 4.

2.5 Pilot 5

Pilots 1-4 will produce both the Digital model and the physical vehicle. Thus, it will be possible to validate the DTs for each pilot separately. On the other hand, it is not possible to validate the P5, thus, it is agreed not to deal with the Digital models of the P5 in this document.

3 Methodology

The digital twin framework covers all the aspects from the generation of the data to securing, pre-processing, storing, processing, visualising of the data etc. Following that, tools for detecting abnormalities and fault states during dynamic operation will be developed in collaboration with WP3. In the proposed high-level architecture, as depicted in Figure 6, the HDV and Infrastructure data is generated by OEMs physical sources whilst the Environment data is generated either from sensor stations deployed within the project or extracted from environmental data streaming tools (e.g., OpenWeatherMap for weather data, Google Maps for road data etc.).

The collection of the data should be transferred in a secure manner without any interruption from outside or data leak, thus, the Secure Multi-Agent System will handle the heterogeneous data flow backbone based on ioFog, the secure data transmission through hardware or software cyber security solutions (e.g. Secure IoT Gateway, Hardware Security Module etc.), and person/node authentication of the parties via security keys, CAN authenticators etc.

The Kafka-based messaging system will serve for handling real-time event processing and data streaming, ensuring that the data is ingested in a scalable and reliable manner. On top of that, the data will be processed and stored according to semantic model in order to serve the DT related services. The static data will be stored in historical database whilst the dynamic data may be stored into the historical database or rather be processed, monitored, used right away by the DT services.

The following services will provide main cloud functionality:

i. Services for Data Query and Management for data monitoring,
ii. Cloud Management Services for Docker container management,
iii. Security and Privacy Management and Identity Management System (e.g., Keycloak, CRYPTaaS, etc.) for authentication and authorisation.

The acquired data will mainly be used by DT services, such as Predictive Maintenance Service, Predictive Control, Fleet Management Service, Cyber-Physical Resilience Service, LCA, TCO etc. Different functionalities will set different requirements for the Digital Twins and data (PdM, TCO, controls). For predictive control and fleet management services there is a need for fast online simulation of different possible scenarios and optimisation of the vehicle use during the operation. For predictive maintenance purposes emphasis, the data quality while the requirement on the simulation time might be less critical, when the data processing, feature extraction and decision making can be done in offline. For LCA and TCO services the gathered data can be processed to several key figures, that describe the operation characteristics of the vehicle and can be used to assessment of life cycles and TCO.

DT calculations will be deployed on the cloud as Docker containers. The results will be shared with end-point applications or stored through Results Gateway (in JSON format). Some of these services will produce AI models which afterwards will be processed by Explainable AI (XAI) Service to present the results in a meaningful manner by using 3D visualisation techniques such as Online Visualisation, Vehicle HMI etc.

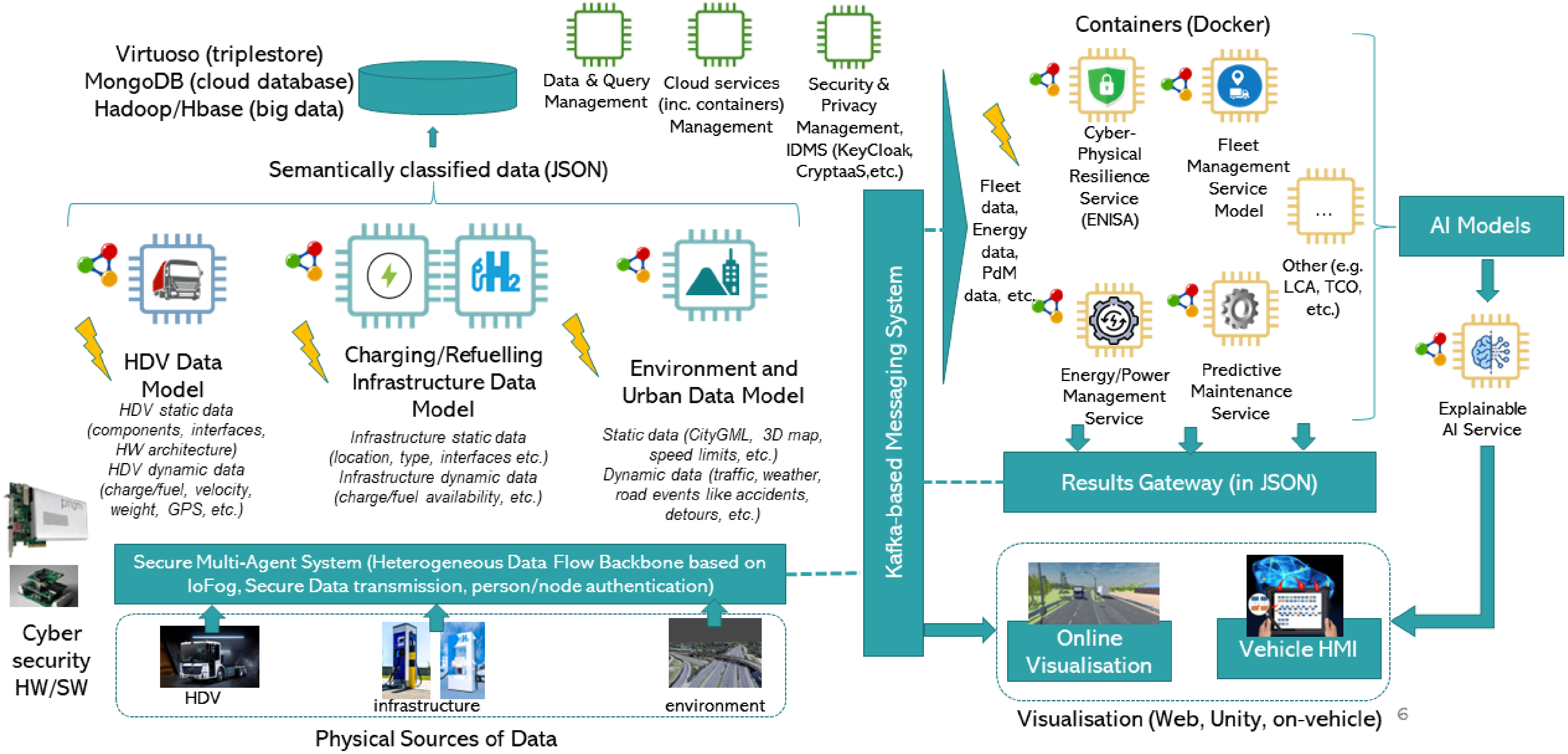


Figure 6. High-level architecture of data sources and digital tool chains.

3.1 Predictive maintenance

Figure 7 illustrates the architecture of predictive maintenance (PdM) within the context of the Pilot Digital Twin. The development of this architecture is designated under project task 5.3. The predictive maintenance algorithm utilizes data collection, pre-processing, feature extraction, and machine learning techniques to effectively detect faults, predict failure, and optimize maintenance schedules for systems. Figure 7Figure 7 describes the data and its relationship with the degradation of the system. The initial crucial step in the predictive maintenance algorithm involves generating data that accurately represents both normal and abnormal conditions, as per the mathematical model specific to each pilot. To make sure that the algorithm is reliable in spotting errors, the data gathering should cover a range of operational situations.

The mathematical models for the components can be supplied by both OEMs and pilots. Besides, developing a mathematical model and estimating its parameters using the existing sensor data offers a viable approach, particularly in scenarios with insufficient data to effectively represent both normal and faulty operations. Failure data can be generated to augment the current sensor data and enhance the performance of the algorithm by recreating this model under various fault states and operating situations. Pre-processing the data after it has been gathered is the next step in order to remove noise and outliers. Additional pre-processing methods may be used to extract relevant features, frequently referred to as condition indicators, from time-domain data by converting it to frequency domain. These condition indicators aid in distinguishing between healthy and faulty conditions.

After extracting relevant features from the data, the subsequent step entails training machine learning models to execute various tasks. Anomalies can be detected, allowing early identification of potential issues. A classifier can be trained to differentiate between different types of faults, providing insights into which component of the system requires attention. Additionally, predictive models can be developed to forecast the systems' degradation path and estimate the time until failure, facilitating efficient maintenance scheduling. Once the algorithm is developed and trained, it can be deployed on the cloud or an edge device for practical implementation. For scenarios with limited data transmission capacity, it's feasible to conduct pre-processing and feature extraction on the edge device and then transmit only the extracted features to the prediction model running on the cloud.

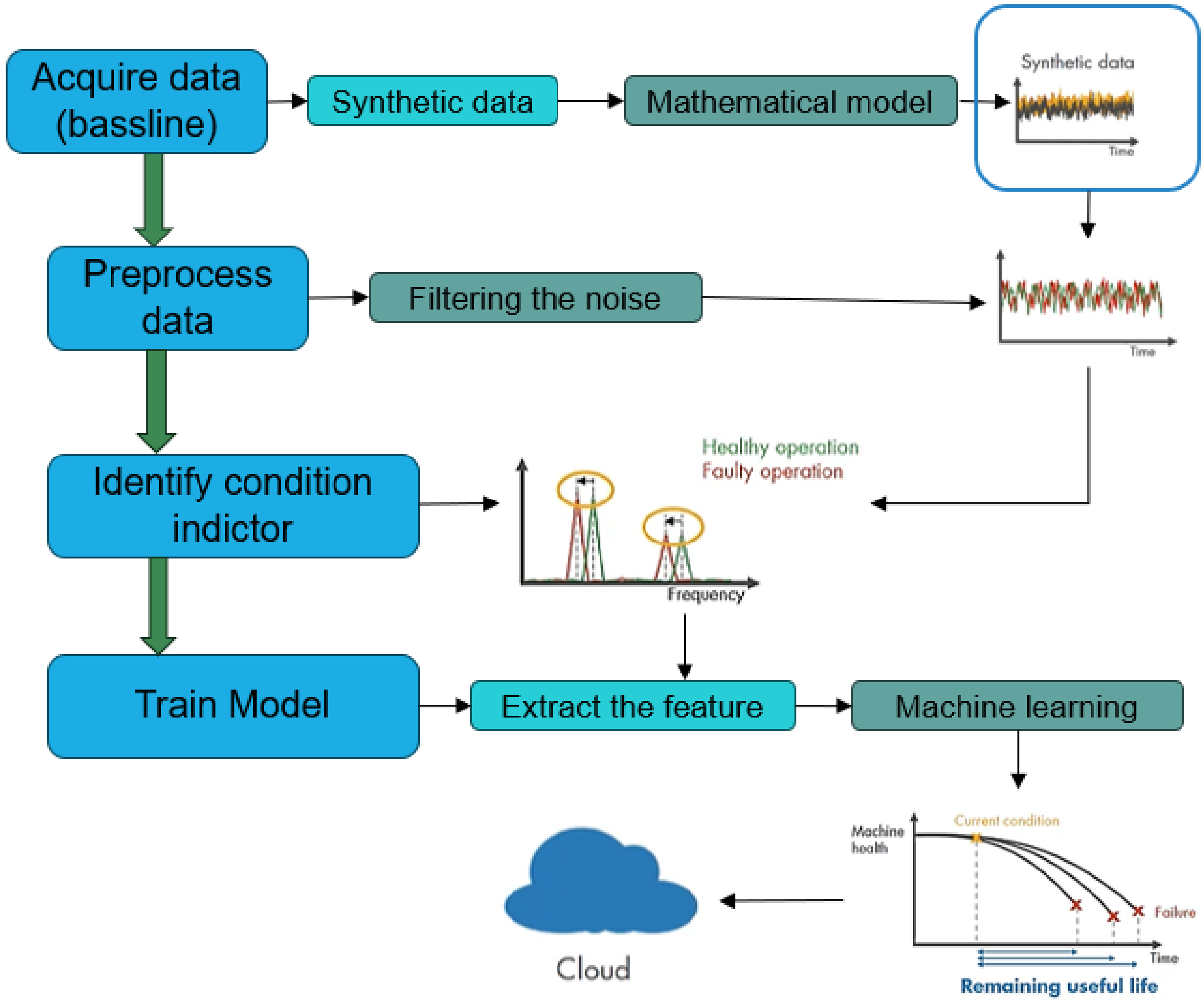


Figure 7. The PdM architecture in the Pilot DT.

One possible algorithm choice for feature extraction is the use of Autoencoders – machine learning architectures composed of an Encoder and a Decoder that learn alternative representations of data, typically with the goal of compressing it into a smaller size. A well-trained autoencoder can discard less important details and retain the most relevant and distinctive features needed to reconstruct the structure of the original data. This enables the algorithm to effectively perform autonomous feature extraction and capture the underlying patterns in the data.

The learned features (commonly referred to as the latent representation) are abstract representations which might not be easily interpretable by humans. However, unlike manually engineered feature extraction methods, autoencoders can learn features that are tailored to the unique characteristics of the systems being monitored, and this adaptability is particularly useful when dealing with large, complex and dynamic models.

In the PdM toolchain, autoencoders can be implemented as feature extraction tools from the data gathered from the pilot models (architecture in Figure 8 below). The initial step involves training an autoencoder using model data that is representative of both normal and failure conditions until the reconstruction is within a defined tolerance for the full training dataset. It is very important to include data from various operating conditions including failure scenarios. Reconstruction of the data from the latent representation is rarely needed, so the Decoder can be ignored once training of the Autoencoder is completed.

After training, the encoder network can be used to extract features from new model data. By utilizing these learned features, subsequent anomaly detection algorithms such as classifiers and predictive models (mentioned above) can focus on deviations in the latent feature space, potentially making the detection process more efficient. Once trained, these models tend to be fast enough to be implemented in an edge device, allowing for the pre-transmission feature extraction.

To create a dataset for training this architecture, data about operating conditions under several failure and non-failure states needs to be gathered and labelled based on their status (normal or failure) and the specific type of failure, if applicable. These labels should then be incorporated into the training data structure.

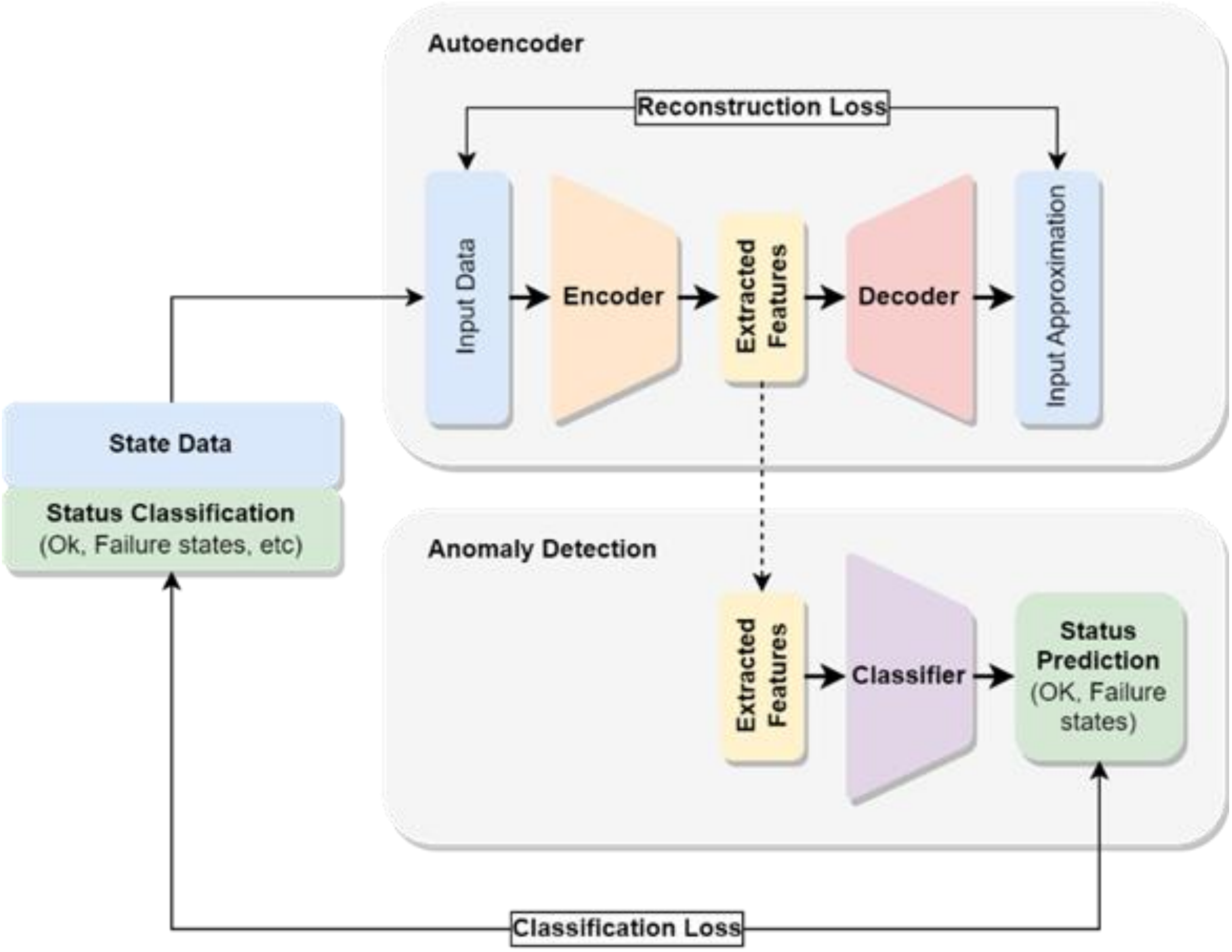


Figure 8. Autoencoder feature extraction architecture.

3.2 Predictive control

In this Chapter a short explanation is given on the methodology of the predictive thermal control (PTC) in the Digital Twin Pilot. The development of the control is going to be done in WP3 and its findings and results will be transferred and implemented in WP5.

The predictive control of the thermal components is intended to enable the reduction of the overall energy consumption of the vehicle's thermal management system. This is achieved by proactive actuation of the individual thermal subsystems and the procedure will also lead to the reduction of component design requirements (power or size of coolant pumps, size of heat exchangers, etc.). Predictive control of the thermal components is part of the "Energy/Power Management Service" block in Figure 6.

For every main thermal component (e.g. fuel cell in its cooling circuit) a virtual thermo-electric representation is the most important part for the predictive control. This model is built and tuned with the help of OEMs, pilots and measurement data from real operation. It must fulfil high accuracy on the one hand, while still be able to compute fast on the other hand, in order to be able to be operated in real-time on the HDV eventually.

In addition to the simulation model, knowledge of the current state of the components or the driving state of the vehicle is particularly important. These data are derived from component and vehicle sensors. Further, navigational data and external data sources i.e. information on traffic flow and on charging infrastructure along the route, etc., should be processed. By combining the all the mentioned sources of information, a future time horizon with details on upcoming demands on the thermal system is generated. The predictive control strategy processes the upcoming demands to set the right control actions at a suitable point ahead of time. Thus, there are interconnections between the predictive control and the "HDV Data Model" and "Environment & Urban Data Model" blocks in Figure 6.

The predictive control will now set the control of the underlying subsystems in an energy-optimal way based on the predicted requirements from the future time horizon, so that there is no violation of the thermal boundary conditions (current and future). For this purpose, the algorithm must be called in a (to be defined) required frequency, parallel to the real driving operation, to be able to compare the current system state of the HDV with the predicted one and to perform the adaptation of the control continuously while driving. In the first step, the predictive control is implemented offline and evaluated and optimized based on historical driving data. If the system achieves the desired benefits in this training operation without violating the boundary conditions, it will be transferred to demonstration operation on a real vehicle/DT.

The reduction of energy consumption of propulsion and thermal conditioning is pursued by using an internal model predictive control approach shown in Figure 9.

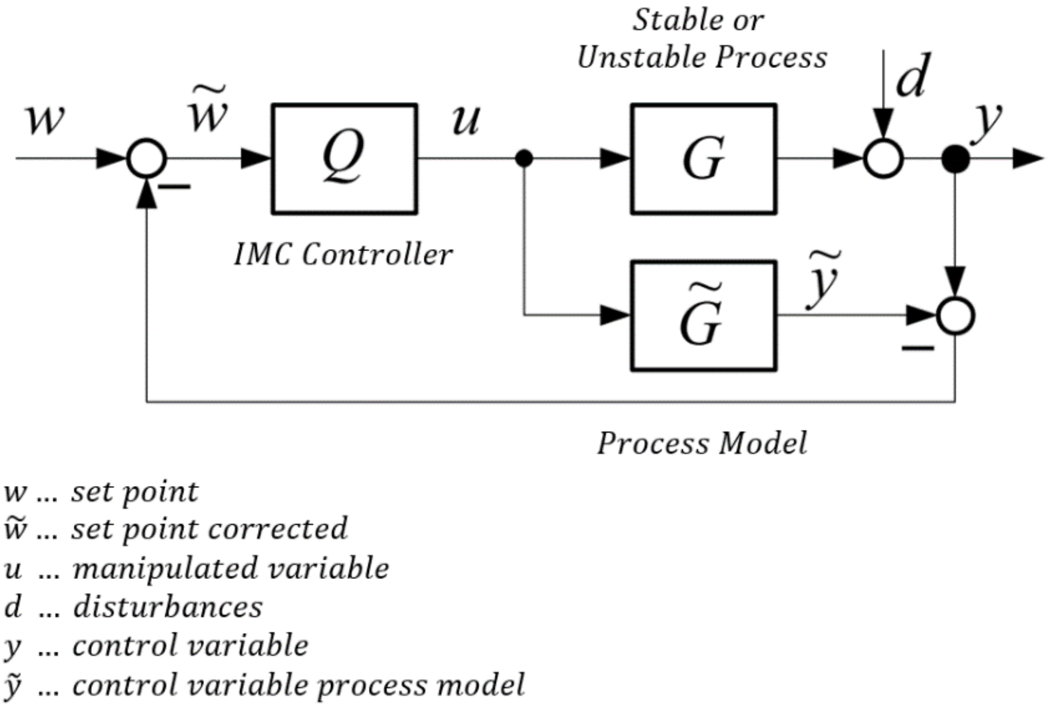


Figure 9. Internal model predictive control framework for PILOT 4.

The model response $\tilde{y}$ is subtracted from the actual response y and the difference, $y - \tilde{y}$ is used as the input signal to the IMC controller. Inside IMC controller an optimizer tweaks the optimum values based on the process model prediction, cost function and constraints. The basis of an IMPC approach is an accurate model of the process as well as known model uncertainties.

3.3 Life-Cycle Assessment as design tool

Life-Cycle assessment (LCA) is used in the ESCALATE project to prevent and minimize the operational environmental impact and reduce the Total Cost of Ownership (TCO) of zero-emission HDVs. Towards this direction, the pilots' technologies, design and components should be optimized for resource efficiency and modularity. Also, sustainability considerations should be integrated into the vehicle's design, architecture, and manufacturing processes, to allow EV manufacturers to identify the most suitable solutions for business needs and budgets, ensuring long-term success in the competitive EV market. The missions planning, and the charging and refuelling infrastructure should also be projected and optimized for reduced costs and environmental impacts. The social aspects like working conditions should be considered since the socio-economic impacts will be also assessed in the LCA. Finally, integration of AI-based predictive maintenance tools to ESCALATE DTs is important for early fault management and enhancement of component life.

4 Digital Twin Requirements for Zero Emission Heavy-Duty Vehicles

In the core of the project are the five use cases i.e., Pilots. In WP2 the baseline planning and requirements are set for each Pilot. The components and systems for demonstrator vehicles are designed in WP3 and WP4. In WP6 the demonstrators of each Pilot will be commissioned, tested and validated. The WP5 studies the digital tools, systems and their interconnection that is needed to ensure smooth and functional design processes.

In order not to make the intended Digital Twins too massive, too vulnerable and suffer incompatibility issues of different tools, it has been decided to divide the project work pilot-wise into Pilot Digital Twins. These would contain all digital models of components and subsystems of each Pilot. A unified digital twin system architecture is presented in Figure 10.

The architecture structure summarises the various vehicle system components and their connections, as well as identifies the differences between the Pilot vehicles. The thermal layout for the HVAC and cooling system is not finally defined yet.

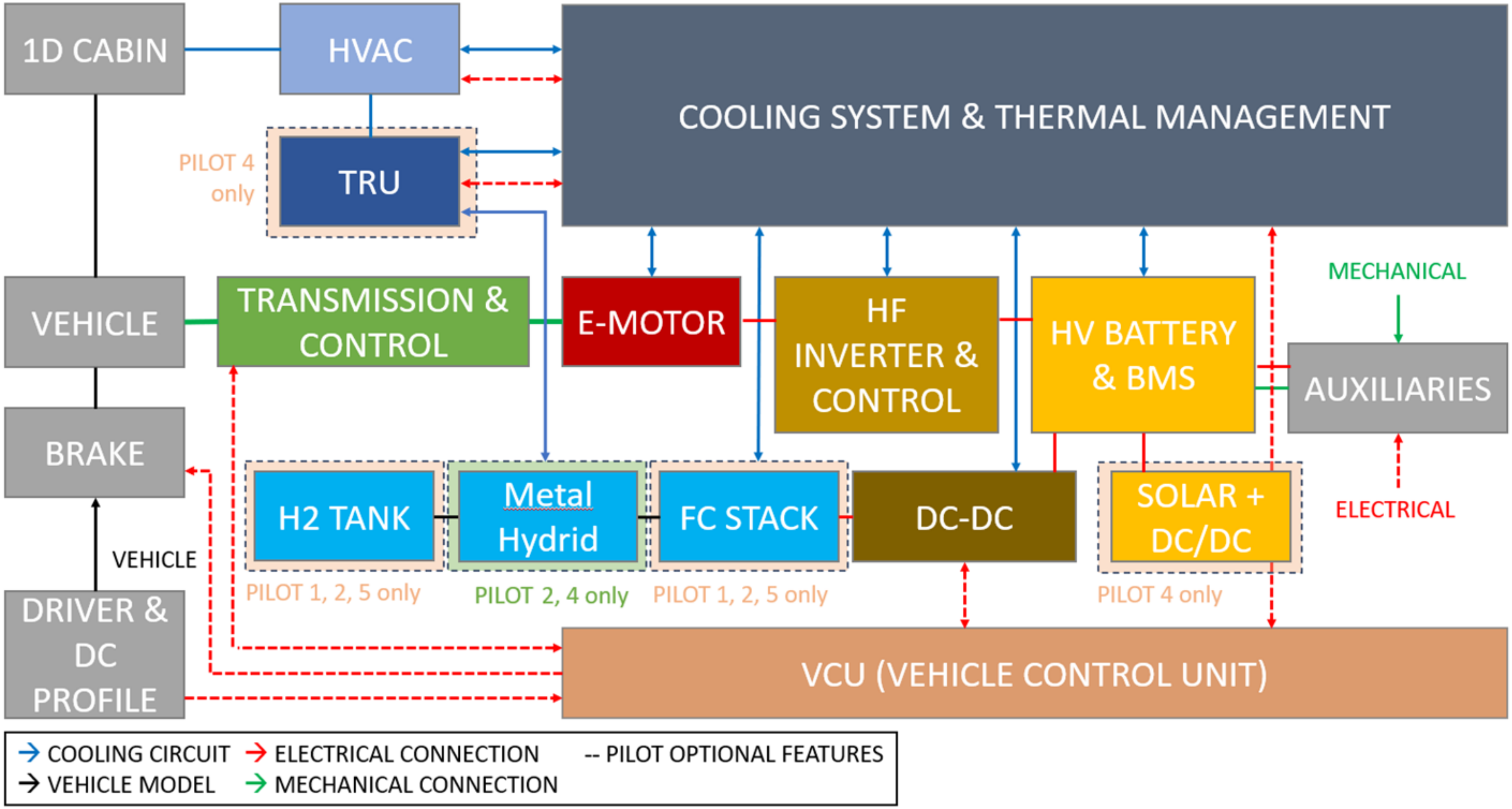


Figure 10. Unified system architecture of PILOTs.

4.1 Real-Time Data Acquisition

The requirements for Real-time data acquisition will mainly be set by the measurements for PdM.

This part is divided into two phases. In the first phase, a contextual framework will be drawn. This framework will be independent from sensors to support any sensors or actuators that will be connected to the truck. In the second phase, sensors will be used and defined variables to be included in the study will be discussed in detail with the transportation operation teams. Due to the fact that the existing vehicles are mostly consuming diesel or gasoline, the data to be collected from such vehicles in operation are going to be followed. Additional knowledge based on data will also be elevated within the scope of the project and will be determined in the second phase. Moreover, the focus will be on transferring the data from all sensors to the remote management as shown in Figure 6. According to the results, appropriate sensor or data transfer protocols will be studied and implemented.

During phases 1&2, a baseline for the predictive maintenance toolchain will be created. This includes identifying the essential tools, libraries, and dependencies required for data collection, pre-processing, and feature extraction. Simultaneously, the framework of the toolchain is modelled, defining its structure and interactions between different components for seamless data flow and efficient analysis.

4.2 Sensing Requirements

For the model validation and calibration as well as optimizing the energy management strategy in real-time the sensing system should fulfil the requirements introduced in Table 1Table 1. Requirements for Thermal System and Thermal Management.. The requirements for sensing will mainly be set by the validation measurements and the measurements for PdM, see Ch. 3.1

Continuous monitoring of temperatures, fluid flow and pressures are essential to prevent overheating and ensure optimal performance of all components in the system. Continuous temperature monitoring of the electric motor(s) must be facilitated to prevent overheating and ensure optimal performance. Fluid temperatures need to be measured to ensure effective cooling/heating and the possibility of real time optimization. The system shall integrate an ambient temperature sensor to adjust thermal management strategies based on external conditions. The position of the sensor must be chosen in such a way that the influence of thermal radiation or thermal bridges is minimized.

In batteries it is essential to continuously monitor and report the battery's state of charge (SoC) and state of health (SoH) to optimize thermal management actions. Monitoring the flow rate of coolant within the thermal management system to ensure efficient heat transfer. This requirement must be fulfilled at least once and for a holistic test procedure to cover all relevant operating conditions and to generate pressure-loss vs. flow-rate mappings.

Continuously monitor coolant/refrigerant pressure at key points in the system is to prevent overpressure or leakage conditions. Especially for refrigerant circuits the pressure sensing is mandatory to operate the thermal system in the correct way. Humidity sensors must be incorporated to assess the ambient humidity, as this can impact cooling efficiency and operating mode.

Table 1. Requirements for Thermal System and Thermal Management.

SENSING SYSTEM	MEASUREMENT POINTS	MEASUREMENT INTERVAL	PRECISION	MEASUREMENT RANGE	UNIT
Battery Pack Temperature	Battery cell, Multiple	Continuous	±0.5	-40 …+150	°C
	Housing air temperature / Multiple	Continuous	±0.5	-40 …+150	°C
	Housing temperature, Multiple	Continuous	±0.5	-40 …+150	°C
	Cooling system, (Inlet/Outlet)	Continuous	±0.5	-40 …+150	°C
Fuel Cell Temperature	Fuel cell stack, Multiple	Continuous	±0.5		°C
	Coolant, (Inlet/Outlet)	Continuous	±0.5		°C
Fuel Cell Voltage	Cell and Stack	Continuous	±0.1/±0.5		V
Fuel Cell Current	Stack	Continuous	±0.5		A
Hydrogen Tank Pressure	Each Tank	Continuous	±0.5		bar
Hydrogen Tank Temperature	Each Tank	Continuous	±0.5		°C
Electric Motor(s) Temperatures	Stator windings, Multiple	Continuous	±0.5		°C
	Rotor windings, Multiple	Continuous	±0.5		°C
Fluid Temperatures of major components	Coolant, (Inlet/Outlet)	Continuous	±0.5	-40 … +150	°C
	Refrigerant, (Inlet/Outlet)	Continuous	±0.5	-40 … +150	°C

SENSING SYSTEM	MEASUREMENT POINTS	MEASUREMENT INTERVAL	PRECISION	MEASUREMENT RANGE	UNIT
Flow Rate of major components	Coolant, Multiple	Continuous	±0.1	Depends on circuit, Mandatory at commissioning, Optional during operation	L/min
Fluid Pressure of major components	Coolant, (Inlet/Outlet)	Continuous	±0.1	Relative, 0 … 10	bar
	Refrigerant, (Inlet/Outlet)	Continuous	±0.1	Relative, 0 … 40	bar
Ambient conditions	Temperature, Multiple	Continuous	±1.0	-40 … +60	°C
	Humidity, Multiple		5	Relative	%
Battery State-of-Charge (SoC)	In each battery cell, Multiple	Continuous	±1.0	0 … 100	%
Battery State-of- Health (SoH)		Continuous	±1.0	0 … 100	%
Integration and communication of sensor	All	Continuous	Real-time		T/F
Measurement response of sensor	All	Max. 1 s		Between actual changes in the response of measured parameter.	s
Fluid level	Coolant, Multiple	Discrete		Full, low, empty	F/L/E

4.3 Simulation Model Requirements

4.3.1 Longitudinal vehicle modelling

The longitudinal vehicle model is made with the system simulation software. The model structure is modular and can be adapted to battery electric vehicles as well as fuel cell electric vehicles. The battery electric model includes several sub models like the mechanical traction power calculation, the electric motor with traction inverter, the battery with DC link and auxiliaries. The Fuel cell electric vehicle model (FCEV) model consists additionally of a fuel cell with DC-to-DC-converter and operation strategy controller. Of course, the models can easily be adapted to other topologies. The input of these models are the vehicles and components parameters and characteristic diagrams. Furthermore, the driving cycle and the gradient profile are needed. The model can output every calculated value for postprocessing but also for connecting with other models (e.g., the metal hydride ref. System model). For coupling with other tools, it is possible to couple the model via FMU coupling.

The longitudinal vehicle model enables the simulation of the truck driving on any route and can be used to define the energy need for driving. The digital twins for all UCs will include longitudinal dynamics and all required VECTO classes are considered, while respective VECTO models will be also setup. Digital twin model of the vehicle is updated for each time step defining the vehicle motion, location, energy levels, and driver actions and so on. Using this updated information, the best possible scenario for the operation is found and applied to the system. Using a fast vehicle motion simulation methodology, the prediction of optimal driving behaviour can be done. This forms the basis to development of advanced energy management for the vehicle drive demand (O1.7, O1.8) and other onboard energy consumers like temperature controller transports (O1.9):

- O1.7: Development and implementation of advanced control and management strategy framework to optimise the operations of hybrid systems (r-HDVs) up to 10%.
- O1.8: Implementation of a novel AI-based energy management algorithm to optimize drive energy demand of b-HDV {MBT}up to 5%
- O1.9: Implementation of an adaptive energy management algorithm to optimize onboard energy both for b-refrigerator HDV {ELCT} considering cooling and f-HDV {BMC} while driving including breaks up to 4%

There are two approaches in the vehicle simulation. The former is the forward approach, also known as the dynamic approach, the latter is the backward approach, also known as the quasi-static approach. Although the backward approach seems to be more precise and requires less computing load, the forward approach gives the closest results to actual results. The forward approach offers the closest experience to real-life conditions, as well as allows examining the dynamic behaviour of the vehicle with only pedal input. It is also much more prone to development in Hardware-in-the-Loop (HIL) environment. The choice between the backward and forward approach will be taken pilot-wise.

In the forward approach, the traction force is calculated first, which will enable the vehicle to reach the desired speed. The electric motor produces this force, and power is transmitted through various mechanical connections. Torque multiplication is made in proportion to the gear ratio while transmitting the generated torque through the gears on the powertrain layout. When it ultimately drives the wheel, the wheel generates a torque proportional to its dynamic radius. On the other hand, there are forces to slow down the vehicle against this torque that drives the vehicle forward. These are rolling resistance, aerodynamic drag force, grade resistance, and inertial resistance, which will be calculated. The net force is found by subtracting these resistive forces from the traction force. Thus, acceleration is obtained by Newton's second equation of motion. An important point in the forward approach is that a driver model is needed for the vehicle to go in the desired speed profile. This driver model is a PI controller that works by giving the accelerator or brake command, if the speed deviation is positive at a time of t, it gives the brake command and if the speed deviation is negative at a time of t, it gives acceleration command to reach required speed level. While this process is taking place, the power needed by the electric motor and other systems is supplied by the battery and fuel cell system, and this is achieved by energy management strategy. The schematic of this process is shown in Figure 11.

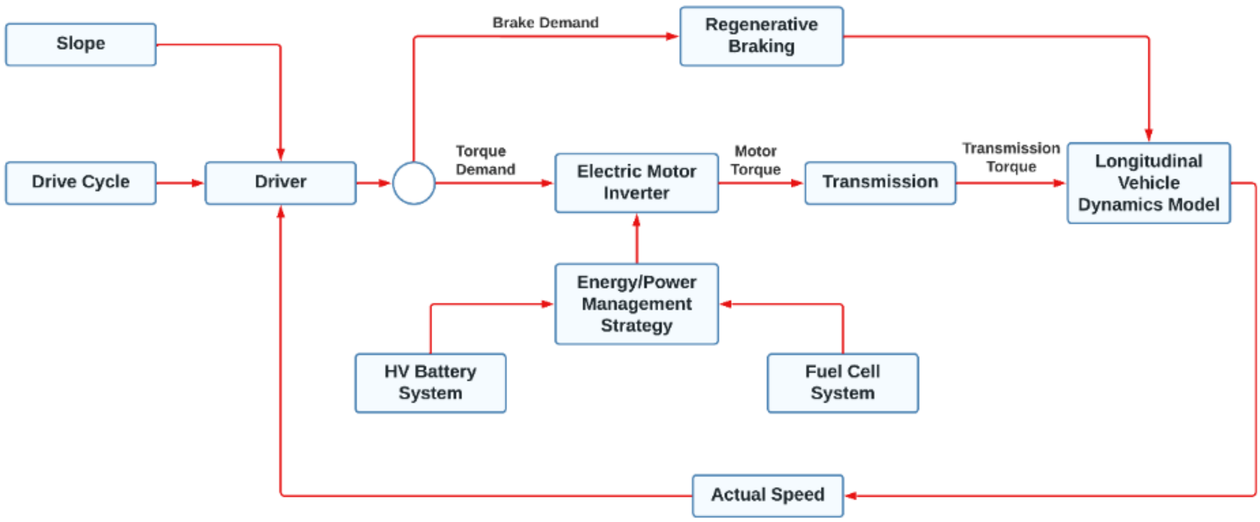


Figure 11. Schematic of the simulation process by subsystems in the forward approach.

In ESCALATE, DT will be used for energy management strategy and optimization of maintenance. In that case, it is more convenient for DT to be based on power/energy analysis. Therefore, the factors that are listed in Figure 12 should be considered. The model will be developed in MATLAB/Simulink environment together with VECTO models and libraries.

The simulation environment runs at least at soft-real-time. (e.g., for PILOT4) The soft-real-time model synchronizes the simulated time with the real wall-clock time. It is achieved by adding a delay to balance the simulation time and the wall-clock time. This reduces drift over long periods. However, some jitter is inevitable on non-real-time operating systems like Windows, standard Linux or MacOS. The clock resolution is limited by Sleep() or usleep() function accuracy, which is around 10ms on Windows and better on Linux or MacOS. The real time usage depends on the services or submodels running on the simulation platform and will be considered depending on the requirements. For submodels with fast decision-making use-cases the simulation runs faster than real-time. Whereas e.g., predictive maintenance tasks allow slower calculation times. For PILOT 4 MATLAB R2023a together with Simulink, Curve Fitting Toolbox, Simscape, Simscape electrical, Stateflow as well as Simulink compiler are used as simulation platform.

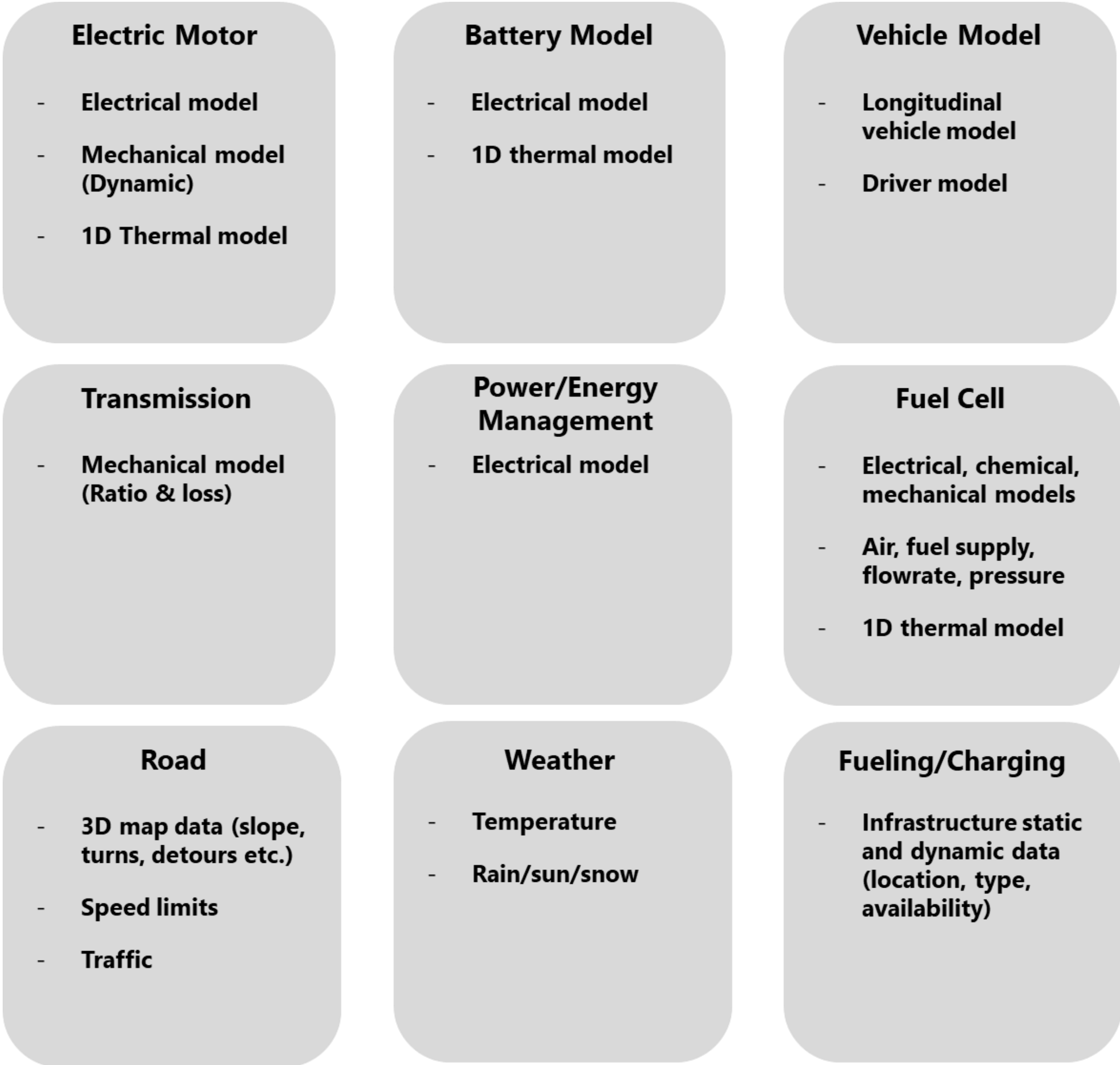


Figure 12. All the factors to be considered for modelling.

4.3.2 Metal Hydride Refrigeration modelling for H_2-Vehicles

The metal hydride cooling system utilizes the kinetic energy between pressure tank and fuel cell system to provide cooling power in a pressure driven refrigeration system. This system is designed for hydrogen vehicles only, as only hydrogen can be absorbed and desorbed in the chosen metal hydrides in an exothermic or endothermic reaction.

Figure 13 depicts, how two metal hydride filled desorbing and absorbing reactors can provide a constant heat or cold flow in two half cycles. Hydrogen is desorbed in Reactor 1 and thermal energy is needed to drive the reaction, which results in a cooling effect. Meanwhile, reactor two absorbs hydrogen from the pressure tank and this exothermic reaction provides heat. When reactor one is desorbed to a degree, where the fuel cell cannot be supplied sufficiently with hydrogen anymore, R1 switches to desorbing mode and R2 to absorbing mode. With this reactor switching, a quasi-continuous cooling and heating effect can be ensured.

The thermodynamic behaviour and the physical absorption and desorption process are described in an equation-based metal hydride refrigerator model which was partly validated with a test bench at DLR. The model needs the inputs introduced in Figure 14 to calculate the cooling temperature and the necessary auxiliary power for valves, coolant pumps and controller and returns a maximum hydrogen mass-flow, based on metal hydride characteristics. Currently, the model is implemented in MATLAB Simulink environment and validated with selected steady state operating points and cooling temperatures between 15 and 25 °C. However, to evaluate energy improvements for refrigeration loads, the cooling temperatures need to be decreased down to -20 °C and transient operating strategies need to be investigated. Therefore, a model coupling between the proposed metal hydride model and the refrigeration system for refrigerated loads should be pursued with FMU for example. In a last step the models can be validated on a Hardware-in-the-Loop testbench with realistic input data from the Pilots.

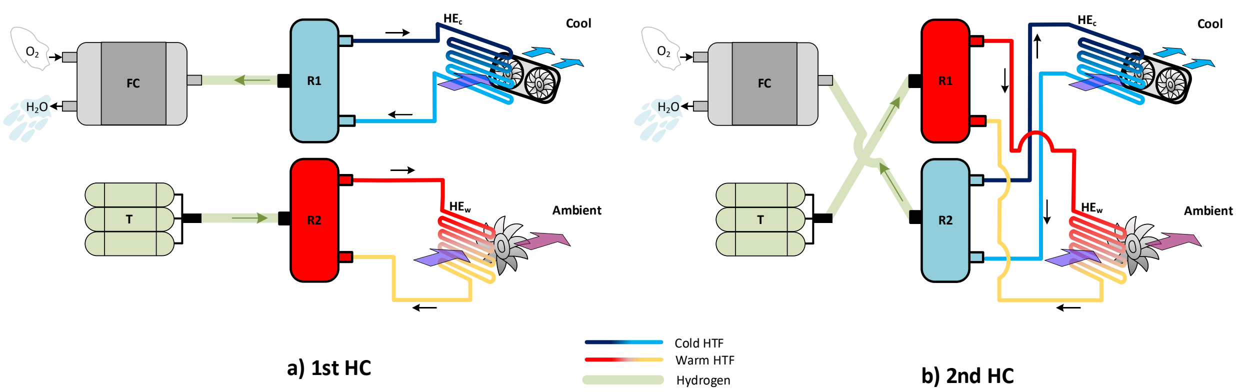


Figure 13. Functional principle of reactor metal hydride refrigerator reactor switching.

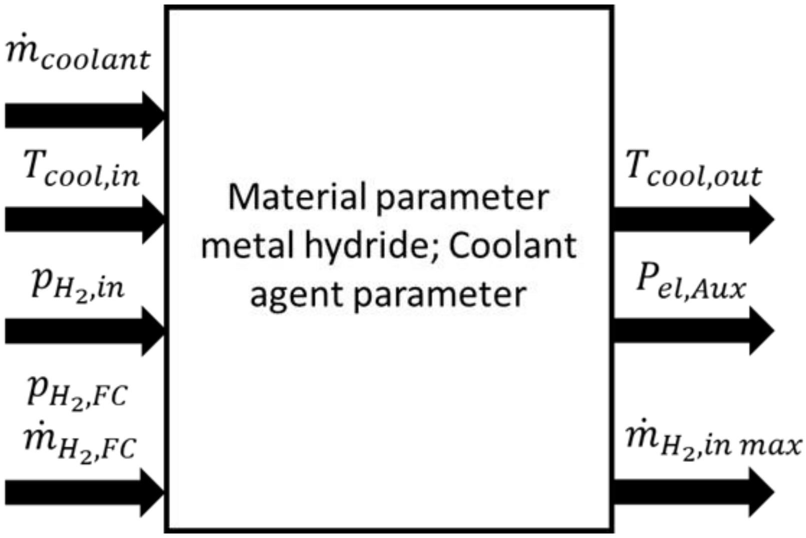


Figure 14. Black box model of metal hydride refrigerator Simulink model.

As this project considers only fuel cell powered vehicle without refrigeration compartment the digital twin of the metal hydride system needs input data from several pilots as mentioned in Table 2. Inputs to validate metal hydride refrigeration system., the fuel cell related date is used from Pilot 1 und 2 and the cooling demand in real life operation is dragged from Pilot 4. A combination of these 3 pilots to assess the metal hydride refrigeration system comes with uncertainties, because a fuel cell refrigeration does not exist in the project. However, more data can be used, by using 3 pilots and not just one pilot, which balances the imprecision of combining 3 vehicles with different drivetrains.

Table 2. Inputs to validate metal hydride refrigeration system.

PILOT	DATA
Pilot 2 (BMC Tuğra)	Hydrogen mass flow, H_2 tank pressure, H_2 fuel cell pressure
Pilot 4 (Electra RS)	Cooling capacity, climatic data (temperature, humidity)

4.3.3 Fuel cell power aggregate modelling

A fuel cell power aggregate in the power range of 100-200kW is being built which can be used e.g., as a single or a twin application in a heavy-duty truck for propulsion. The model-build up bases on the equivalent circuit approach of a PEMFC. The electrochemical FC state for this 1-zone analytical modelling method will be calculated. The model should allow a fast calculation time (minimum 10 times faster than real-time) as well as follow up as basis to investigate several powertrain layouts and control strategies at all relevant boundary conditions e.g., temperatures, road profiles, driver characteristics etc.

The FC model shown in Figure 15 should be based on the FC specifications supplied by Ballard (BLRD) in ESCALATE. It will be evaluated with data from Ballard, e.g., FC power plotted versus FC specific currents. Additionally, temperature influence must be considered. The model should correctly illustrate Begin of Life (BOL) and End of Life (EOL) Characteristics.

VIV will share the model in a protected FMU with relevant partners.

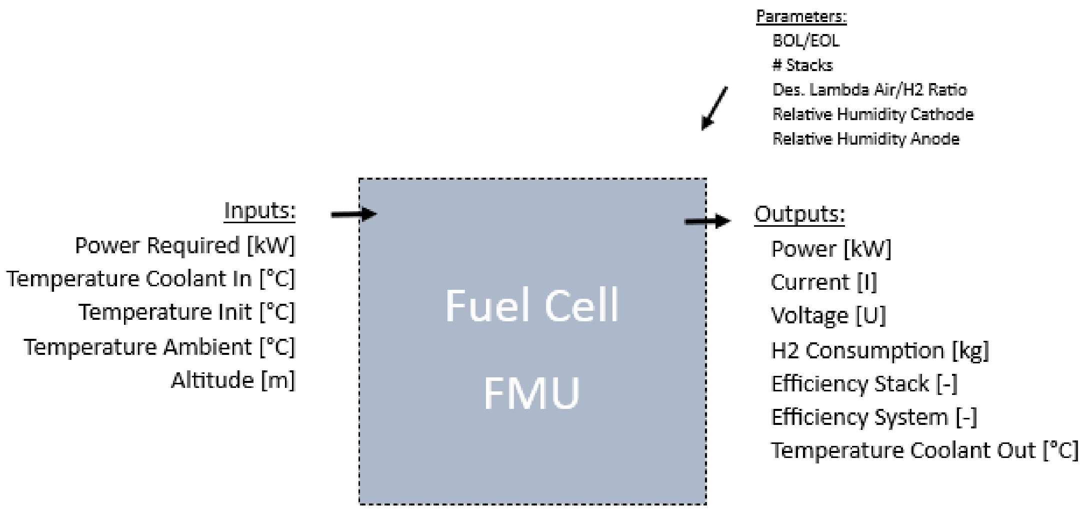


Figure 15. Black box model of fuel cell FMU.

4.3.4 High voltage battery modelling

The battery model generated must be capable of real-time output production, while maintaining a strong fidelity to the real system. This is achievable by parameterizing the battery response curve to the multitude of scenarios expected from it, from charge and discharge at different temperatures, to different C-Rates. Extracting from the battery pack 1st order electrochemical dynamics will grant the right balance between accuracy and computational effort.

A capable model will have thermal and aging considerations coupled to it, allowing battery degradation prediction over time, better maintenance scheduling and reduction of operational impact.

The models will then relate to the rest of the components developed for the Pilot in study. In Figure 16 a black box schematic with the expected input/output variables is presented.

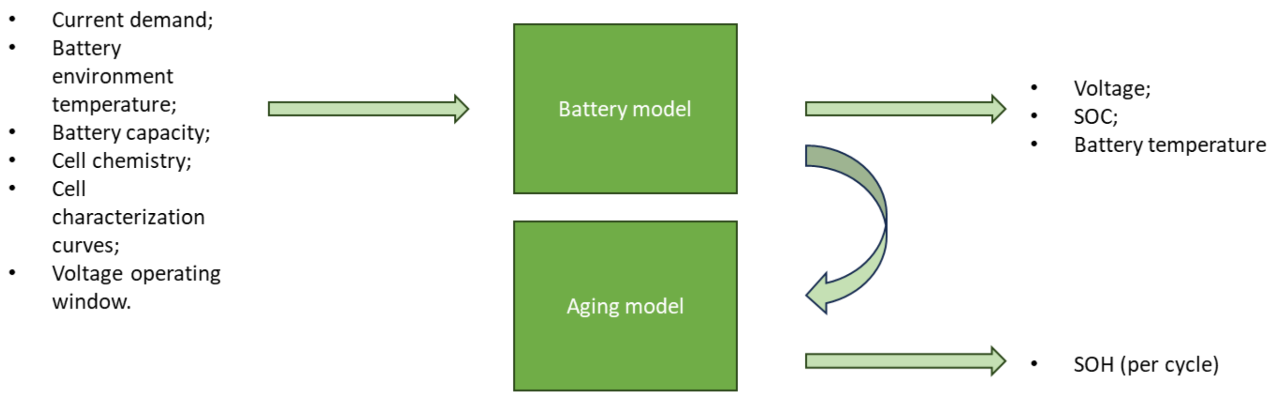


Figure 16. Black box schematic of the high voltage battery model.

4.3.5 Environment

The digital twins for all UCs will include simplified description of the vehicles' operating environments, as the main goal is to study the energy/power consumption as well as duration related phenomena (maintenance). Thus, there are not so many requirements for modelling the environment. One important part of the environment is the charging/refueling infrastructure that will be studied in WP4. However, the simulation of charging/refueling events are not in the project scope. They are described simply as scalar value of energy transmitted to vehicles.

4.4 Requirements of the Fleet Operators

In Table 3 and Table 4, the requirements for parameters to be measured for purposes of validation of the digital twins are presented. Respectively, these parameters can also be generated by simulating the DTs, e.g. vehicle longitudinal model can generate data for the TCO and LCA analyses. The measurements will take place in WP6 in which the demonstrator vehicles (Pilots) are deployed. The vehicle parameters are inherited as requirements throughout the whole vehicle design cycle (WP2, WP3, WP5) while the parameters for operating side will mainly be of interest in infrastructure design in WP4. Naturally, the WPs are interlinking feeding the ones' results for input for others.

Table 3. Fleet Manager Requirements for vehicle side

REQUIREMENTS	UNIT
Efficiency	kWh/100km
Operational Costs	€/km
Purchase Costs	€
Maintenance	€/a
Freight Volume	m^3
Freight Weight	kg
Productive Time per Day	h
Preparation Time	h
Lifetime	km
CO_2-Footprint	g CO_2/km

Table 4. Fleet Manager Requirements for operating side

REQUIREMENTS	UNIT
Operating Scenario	-
Daily Operating Range	km
Number of Stops	-
Duration of Stops	h
Location of Stops	Lat/Lon
Payload Volume	m^3
Payload Weight	kg
Optional (to be discussed in WP6):	
Current truck location	Lat/Lon
Current Truck Status	Available, Busy, Out of Order
Time of availability/occupation/maintenance	h
Time window for stop	Date, Datetime

In some Pilots, the Time window for stops i.e., when should the pick-up/drop-off happen (date range or time slots) would be feasible to collect appropriate validation data.

4.5 Real-Time Monitoring

To develop and implement a fleet management tool in WP5 some input data is needed. This includes real-time data from vehicles of the existing fleets during operation:

- GPS position (Lat/Lon)
- gradient or altitude
- vehicle velocity
- power demand at the wheels
- power demand of the powertrain components (ICE, EM, Battery, FC)
- power demand of the auxiliary components
- lateral and longitudinal acceleration
- energy storage related values (SoC, tank level, fuel consumption)
- ambient temperature
- component temperatures
- freight weight and volume over time

Most data should be available as a CAN signal and retrievable via a CAN logger. Values that are not available as a CAN signal must be gathered using additional sensors.

The obtained data will be used to extract relevant vehicle routes and target locations of the fleet. Furthermore, fleet operator-specific data will be used to optimize the composition of the next-generation mixed or pure ZEV fleet and show their potential.

As a side benefit, the data also enables the generation of realistic driving profiles that can be used in WP3.4 for mission-specific powertrain component dimensioning.

The solar conditions could be beneficial for the Pilot 4 use-case. Time stamp information is also relevant, especially when considering seasonality or time of day for solar exposure.

4.6 Simulation and Predictive Analytics

T5.3 targets an AI-powered multi-domain tool chain for predictive maintenance (PdM). A reduction in the rate of cost is intended, and the future behaviour of the system based on the actual test is suggested to predict lifetimes and reduce future fatigue. The major goal is forecasting maintenance based on multiple degradation models, failure scenarios, and system lifespans from the project demonstrators. The major components (ESS, FC, PE, EMs, etc.) will be identified, and their health status will be determined. Toolchain interfaces will be set up based on the requirements from T5.1 for all UCs.

Regarding the PdM toolchain, the effective predictive maintenance strategy is vital for ensuring the reliable and efficient operation of powertrains in electric trucks. By following the outlined phases, operators can harness the power of data-driven insights to optimize maintenance schedules, reduce costs, and enhance the overall performance of electric truck fleets. Predictive maintenance is instrumental in ensuring the reliability and efficiency of powertrains used in ESCALATE project.

4.6.1 Phase 1&2: Toolchain Baseline and Framework Modeling

The initial phase involves creating a baseline for the predictive maintenance toolchain. This includes identifying the essential tools, libraries, and dependencies required for data collection, pre-processing, and feature extraction. Simultaneously, the framework of the toolchain is modelled, defining its structure and interactions between different components for seamless data flow and efficient analysis.

4.6.2 Phase 3: Scaling up to the System Level

In this phase, the predictive maintenance toolchain is scaled up to cater to the needs of powertrains at a system level. Ensuring scalability allows for effective management of maintenance tasks across an entire fleet of electric trucks, optimizing the overall maintenance process.

4.6.3 Phase 4: AI-powered Toolchain Validation and Outcome Assessment

AI-powered algorithms are integrated into the toolchain to validate its compatibility with powertrain requirements. The AI component enables efficient prediction and assessment of maintenance outcomes, by providing valuable insights for optimal decision-making in maintenance actions for following requirements:

- O1.5: Implementation of a predictive thermal management algorithm to optimize thermal and drive energy demand while driving and during breaks up to 5%
- O1.10. Demand-driven, predictive energy management of drivetrain considering cabin climatization to increase overall efficiency and hence range up to 5%.
- O1.11. Development of a predictive operating strategy to support the achievement of a minimum energy efficiency of 44 % in FC "charge sustaining mode" and to increase vehicle performance under thermal critical situations by at least 10 %.

4.7 Communication and Connectivity Requirements

The communications and connectivity requirements shall be implemented for the designated digital twins and fleet management applications. The partners responsible shall access and service the data to the digital twin and fleet management implementations which supposedly have various requirements in terms of parameters, access speed and methods etc. due to their internal structure.

The connectivity module shall be designed for three pilot HDVs of the specified manufacturers, i.e., Pilot 2 (BMC Tuğra), Pilot 3 (Mercedes-Benz e-Actros) and/or Pilot 4 (Electra RS). In addition, the design and implementation for connectivity module in Pilot 1 (Sisu) will be discussed.

For the digital twin implementations, it is proposed to utilize the Pilot HDVs and their components as presented in Table 5. The selection of Pilot HDVs and the related components might change depending on the discussions among the participants of WP5. Each use case for the digital twin shall serve for a different purpose to avoid overlapping in studying components and systems.

Table 5. The connectivity implementation for the pilot cases and the fleet management.

PILOT AND RESPONSIBLE PARTNER	COMPONENT	PURPOSE
Pilot 1 (SISU)	Battery	Energy management Battery health monitoring
Pilot 2 (BMC Tuğra)	Fuel Cell	Energy management
Pilot 3 (Mercedes E-Actros)	Electric Motor	Energy management
Pilot 4 (Electra RS)	Battery / Refrigerator	Energy management Detecting battery useful lifetime

4.7.1 Communications and Connectivity Hardware Requirements

The requirements for the connectivity module are listed in Table 6.

Table 6. Connectivity module requirements

CONNECTIVITY MODULE REQUIREMENTS	DESCRIPTION
Data input	Read the information from at least two CAN-Bus lines / OBD port or designated interface specified by the Pilot HDV manufacturers together
	Receive geographical location data from the GNSS satellite systems, namely GPS and GLONASS
	Support two digital inputs with ignition detection
Accuracy	Provide geographic position accuracy of around 2.5m
Data communication	Transmit data via LTE wireless telecommunication standard 4G
Memory	Contain internal volatile memory (RAM)
Physical operation environment and protection	Be physically protected by the protection level IP54
	Operate between -40ºC and +85ºC
Connectivity	Have access to CAN-Bus and J1939 standard buses
	Support configuration via SMS/GPRS and firmware updates
EMC requirements	Pass electromagnetic certification tests, CE/ECE R10

4.7.2 Communications and Connectivity Software Requirements

The communications and connectivity module software requirements are listed in Table 7.

Table 7. Connectivity module software requirements

CONNECTIVITY MODULE SOFTWARE REQUIREMENTS	
Support for standardised interfaces/protocols	MQTT over TCP/IP communication protocol
	Over the Air (OTA) update via HTTP/HTTPS protocol
	TLS protocol for data transport security
	Binary serialization communication protocol for data security and privacy reasons
	JSON messaging format
	REST API
Software shall provide	Configurable geofencing
	Configurable alarms
	Configurable message filters to transport vehicle network data
	Nearly real time communication via 4G cellular communication
Vehicle gateway shall support	CANbus connection for in-vehicle communication
	V2N (vehicle to network) communication (e.g., ModBus, WiFi, GPRS, 4G, 5G, Ethernet, etc) to enable V2C (vehicle to cloud) communication.

In addition, the connectivity module software should be capable of transmitting in-vehicle CAN-Bus network for 1 Mbit/s with a maximum %50 busload.

4.8 Cloud Infrastructure Requirements

Creating a cloud infrastructure for Zero-Emission Heavy-Duty Vehicles (HDVs) involves catering to the specific needs of these vehicles, including data management, real-time monitoring, emissions tracking, and efficient charging. The cloud infrastructure requirements tailored to support such vehicles are presented in Table 8.

Table 8. Cloud infrastructure requirements for HDVs.

REQUIREMENT	DESCRIPTION
Scalability and Elasticity	Design the cloud infrastructure to scale horizontally to accommodate a growing fleet of Zero-Emission HDVs. Implement auto-scaling to dynamically adjust resources based on demand, ensuring optimal performance during varying loads.
Real-Time Telemetry	Enable real-time data ingestion and processing to monitor vehicle parameters like battery status, energy consumption, and vehicle location. Utilize technologies like MQTT or WebSocket for efficient real-time data streaming from vehicles.
Geographic Distribution	Deploy cloud resources across multiple geographic regions to minimize latency and ensure efficient communication with HDVs in different areas.
Edge computing	Implement edge computing capabilities to process critical vehicle data close to the source, reducing latency and optimizing bandwidth.
Data Storage and Management	Utilize cloud databases to store vehicle telemetry data, maintenance records, charging history, and emissions information. Consider NoSQL databases for handling large volumes of unstructured and time-series data
Data Security and Privacy	Implement robust security measures to protect vehicle data, ensuring encryption, access controls, and compliance with data privacy regulations.
APIs and Integration	Develop APIs that allow seamless integration between the cloud platform and onboard vehicle systems, charging infrastructure, and third-party services
Real-Time Analytics	Implement real-time analytics to process and analyze vehicle data as it arrives, enabling immediate insights into vehicle performance and emissions

REQUIREMENT	DESCRIPTION
Battery Management	Design a module for battery management, monitoring battery health, state of charge, and managing charging cycles efficiently
Emissions Monitoring	Create mechanisms for tracking vehicle emissions data, calculating carbon footprints, and providing emissions reports for regulatory compliance
Charging Infrastructure Integration	Develop modules to integrate with charging station networks, managing charging sessions, energy consumption, and billing
Containerization and Orchestration	Utilize containerization technologies (e.g., Docker) and orchestration platforms (e.g., Kubernetes) for efficient deployment and management of cloud services
Cloud Service Providers	Choose a cloud provider (e.g., AWS, Azure, Google Cloud) that aligns with your platform's requirements, scalability needs, and budget.
High Availability and Disaster Recovery	Design for high availability by distributing components across multiple availability zones and regions to minimize downtime. Implement backup and disaster recovery strategies to ensure data resilience and quick recovery in case of failures
Data Visualization and Reporting	Develop user-friendly dashboards and reports for vehicle owners, operators, and administrators to monitor vehicle data, emissions, and charging status.
Regulatory Compliance	Ensure that the cloud infrastructure supports compliance with emissions regulations, data privacy laws, and industry standards
Monitoring and Alerting	Implement monitoring tools to track the health and performance of cloud resources, services, and vehicle data processing pipelines. - Configure alerts for anomalies, resource constraints, and system failures.

By addressing these cloud infrastructure requirements, you can create a robust and efficient platform that supports Zero-Emission HDVs, promotes sustainability, and enables effective fleet management and predictive maintenance.

4.9 Data Security and Privacy Requirements

A user shall be authenticated and authorised before using a DT function/operation/API. Preferred method is to use multi-factor authentication which complies with FIDO standard.

The DT system shall comply with end-to-end vehicle-grid / cloud communication resilience requirements according to Table 9.

Table 9. DT system requirements

DT SYSTEM SECURITY REQUIREMENTS
The overall system should comply **with ENISA threat taxonomy, safety and cyber security standards and UNECE 155/156 regulations.**
The resilience of the overall vehicle-to-grid/cloud security must be improved by end-to-end and hardware-based security that will be implemented by the HSM and the Secure Gateway.

The vehicle shall include Secure Gateway for data encryption during data transmission that shall support CANbus connection and 4G or ethernet connection (in case the vehicle has its own online connection)

The cloud shall include Hardware Security Module (HSM) (SoftHSM or HardHSM) for data encryption and decryption, RNG generation, digital signature, and other cryptographic operations. The HSM shall comply with FIPS, NIST and/or ANSI standards.

4.10 Fleet Management Tool Requirements

The fleet management tool has inputs and outputs that must be visualized for the user. On the input side, the values can be categorized as in Table 10 :

Table 10. Fleet management tool inputs

CATEGORY	INPUT
Infrastructure (depot, customers (warehouses, …) and existing charging locations)	GPS position (Lat/Lon)
	required goods (pickup/delivery)
	required service time
	origins and destinations of picked up goods
	available charging power
Considered vehicles	ZEV (Pilot 1 – 5)
	Conventional ICE vehicle

The output values can be categorized as in Table 11

Table 11. Fleet management tool outputs

CATEGORY	OUTPUT
Infrastructure (depot, customer (warehouses, …) and potentially additional charging locations)	GPS position (Lat/Lon)
	actual picked up/delivered goods (weight and volume)
	used time frame
Optimized fleet data	Composition
	Overall operational/standstill time
Optimized route data (fleet related and vehicle specific)	GPS trajectory (Lat/Lon)
	Altitude profiles
	Estimated vehicle velocity profiles
	Operational/standstill time
	SoC/Fuel level curve

4.11 Scalability and Modularity Requirements

The sub-models used in the Digital Twins should and will be scalable to support the modular drivetrain design in WP3. Therefore, electrical components, e.g. the battery and fuel cell, are modeled on cell level to allow a modular interconnection to realize various component sizes. Mechanical components, e.g. the electric motor, can be scaled in their size via correlations in terms of torque, speed and power. Thermal components, e.g. the radiator, are modeled based on physical equations. This allows them to be freely scaled in size without losing plausibility.

5 Design and Architecture of Digital Twin Platform

5.1 Integration with Vehicle Components and Systems

Predictive control strategies will be improved by e.g., easier modelling and lower barriers for integration, towards better resilience (valid for all relevant boundary conditions and self-adapting) based on a predictive algorithm and to reduce energy consumption in these major areas (propulsion and conditioning). Postprocessing will allow showing clear the overall benefit compared to conventional control systems (state machine with PI-control).

5.1.1 Functional Mock-up Unit

In Figure 17, the FMI-Standard is introduced (The Modelica Association Project FMI, 2022). A software-independent solution for the model exchange needs to be considered to ensure the modularity aspect of a digital twin. Different dynamic models or submodels from various software platforms are exchanged with the common FMI 2.0 standard. This often-called functional mockup unit, or FMU, is a model exchange or co-simulation tool designed to replicate the functionality of a model through a closed block. The user can integrate this closed block with other components or other FMU blocks by predefined inputs/outputs and parameter. FMU blocks should have sample times with divisible intervals that produce whole numbers.

For PILOT 4, the FMU step size should be in a range of 6×10^{-4} – 0.1s. The step size needs to be fixed. The Figure 17 shows an illustration of a FMU block. U is defined as the input and y as the output. The user defines the parameters p and local variables w and the solver calculates the equations inside the FMU based on continuous states, the time and the event indicators.

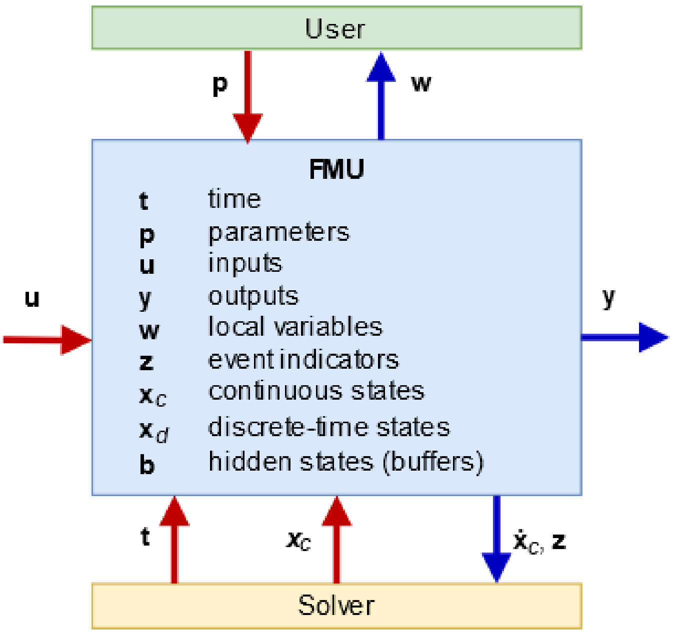


Figure 17: FMI-Standard.

6 Validation of the Digital Twin Platform

The predictive control strategies developed in WP3 will be tested and validated virtually using a software-in-the-loop test procedure. For this purpose, the required input data of the real vehicle will be logged during actual driving. The required input data is listed in Table 12.

Table 12. Input data for digital twin

INPUT DATA TO DIGITAL TWIN LOGGED FROM REAL VEHICLE
Vehicle velocity
Gradient or altitude
Ambient temperature
Power demand wheel
Battery SoC
Hydrogen tank level
Component temperatures
Power demand of auxiliary components
Travelled distance and/or GPS coordinates

The Software-in-the-Loop test procedure also enables comparison of the predictive control strategies with rule-based strategies. Since most of the pilot vehicles will use off-the-shelf-components, the results can also help to highlight the potential of future vehicle configurations.

Virtual testing will be done with DT to assess and optimise control strategies against various mission profiles including the VECTO regional and long-haul driving cycles, as well as considering the hardware selection of powertrain design (WP3). Models are also integrated into the fleet manager via the usage of the flexible structure of a composite fleet twin (T5.2). Results are validated and comprehensively reported and shared through the consortium to push overall development in an early phase. ERG, AI4 and ORT will contribute to the development of cloud and connectivity.

7 Conclusions

This document describes the specifications and requirements for the trustworthy digital toolchains of Modular Digital Twins for demonstrator vehicles including cost-effective standardized modular and scalable electric powertrain components for heavy-duty long-haul applications. This includes the computational platform architecture, simulation model methodology, and toolchain selection as well as data management. The requirements and architectures to match with the objectives set for the project have been defined. The operation and the performance of vehicles can be studied using Digital Twins (DT). The scalability of DTs has been discussed.

Simulation tools and DTs are utilized in the project during the vehicle powertrain development to reach and ensure the performance of the vehicles and powertrains. Different mathematical models e.g. longitudinal vehicle model, thermodynamic model and models of fuel cell and battery system have been introduced. The interfaces between functionalities and sub-models of digital twins have been discussed.

Using the DT system and the AI application the vehicle operation is reaching high energy efficiency on vehicle and fleet level and reliable operation using predictive maintenance functions. DTs will be used for life-cycle analysis, for estimating the total operating costs, for predictive maintenance and to design predictive control for thermal systems. Data generation and analysis using DTs have been defined to support the design and piloting of physical demonstrator vehicles.

As the project output will serve a set of four (nr. Pilots) digital twins of the vehicles (incl. components, subsystems, and functionalities). The DTs are not interchangeable between use cases P1-P4, but each Pilot will form its own entity.

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8 References

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The Modelica Association Project FMI. (2022). *Functional Mock-up Interface Specification*. Retrieved from https://fmi-standard.org/docs/3.0/