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Trustable architectures with acceptable residual risk for the electric, connected and automated cars

Deliverable	**Report on requirements for fault detection in actuators and propulsion systems**		
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0.3	20.05.2021	INRIA	Integrated demonstrator descriptions from AVL, BUT, TUDR, and TUG.
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1.0			Final and reviewed Version

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Table of contents

1 Executive/ Publishable summary

This document provides an overview of the requirements on actuators and propulsion systems defined for the four demonstrators considered in supply chain two (SC2).

2 Non publishable information

N.A. (The dissemination level of this deliverable is public.)

3 Introduction & Scope

3.1 Purpose and target group

This report is the outcome of task T1.2 (Requirements for fault detection in actuators and propulsion systems). The purpose is the definition of tasks-specific and application-specific requirements, both categories of requirements being obtained by considering knowledge available in fault detection, failure modes, and residual risks of the partner organizations involved, and the one from the application domain. This document summarizes the requirements to be used within SC2.

3.2 Contributions of partners

The four demonstrators of SC2 are led by BUT, AVL (with contributions from INRIA and TUG), TUDR (with contributions from BUT), and DATA, respectively.

TABLE 1: CONTRIBUTIONS OF PARTNERS

Chapter	Partner	Contribution
6	AVL	System analysis for failure modes potentially occurring in battery electric vehicles, focusing on a thermal controller of a battery, for which a simulation environment is provided. From this system analysis requirements are derived to apply a MonDev for safety prediction.
5	BUT	Requirements and specification of predictive diagnostic system to be running online in the power train inverter controller. Use existing measurements of the quantities required for motor control and carry out additional measurements with special timing, which enables to monitor progress of switching and its degradation as well as the fluctuation of DC bus voltage. The inverter's health state is continuously evaluated, stored in volatile memory, and used for maintenance forecast.
8	DATA	Provide a function during the development and test period alongside the V-Model. Simplify safety and security by applying the OSAM design method to reduce residual risk and optimize quality of code. Use the tunnel effect as a sophisticated method for inspection on chip level.
6	INRIA	Formal modeling of the behavior of the battery thermal control. Contribute to the formalization of requirements using qualitative and quantitative properties interpretable on the model.
7	TUDR	Requirements of health monitoring systems for electric motors, especially to detect mechanical stress and aging effects of the bearings caused by changed behaviour of rotating components.
6	TUG	Requirements of model-based diagnosis systems in the context of actuators and propulsion systems considering available publications. Contribute to the formalization of the obtained requirements.

3.3 Relation to other activities in the project

The requirements presented in this document provide a description of the demonstrators studied in SC2. Therefore they do not use results of other work packages or supply chains, but rather provide the bases for *all* the further tasks related to SC2.

Nevertheless, the requirements were elaborated in interaction with the similar tasks of the other supply chains (i.e., T1.1, T1.3, T1.4, and T1.5). Inspiring discussions during the (virtual) work-package meetings helped to clarify common objectives and importance of key concepts, such as the residual risk. In particular the interaction with SC5 helped in identifying the relevant standards for the four demonstrators described in the present document.

3.4 Main objectives and key targets overview

The work described in this document contributes to the following main objectives and key targets of the ArchitectECA2030 project.

O1 - Continuous robust design optimization for each part in the ECS value chain (Technical): Related to ensuring secure connected, cooperative, and automated mobility and transportation; and managing critical, autonomous, cooperating evolvable systems. The outcome is robust mission validated design. The objective's KPI addresses coverage components.

O2 - Framework for safety validation of ECS value chain (Technical): Related to managing critical, autonomous, cooperating, evolvable systems; managing complexity; and increasing compactness and capabilities by functional and physical systems integration. The outcome is accepted residual risk in ACS for HAD to enable type approval. The objective's KPI addresses coverage validation.

O3 - Identification and management of residual risks over the entire ECS value chain (Technical): Related to ensuring secure connected, cooperative, and automated mobility and transportation; and reliability and functional safety. The outcome is accepted monitoring device methodologies. The objective's KPI addresses coverage qualification.

O4 - End-user acceptance by trustworthy ECS value chain (Value): Related to ensuring secure connected, cooperative, and automated mobility and transportation; and secure, safe, and trustable connectivity and infrastructure. The outcome is usability. The objective's KPI addresses coverage test.

O5 - Zero emissions, crashes, and congestions by ECA2030 vehicle (Value): Related to ensuring secure connected, cooperative and automated mobility and transportation; and increasing compactness and capabilities by functional and physical systems integration. The outcome is sustainability. The objective's KPI addresses energy efficiency shorter validation time.

KT1 - Architectures, components, sub-systems enabling virtual development and validation (monitoring device, failure risk): Currently no agreed development framework exists to certify SAE L3+ automated driving functions in unstructured environments and adverse weather conditions using virtual validation methods. The reduction of the validation process compared to a mileage accumulation driven approach will be shown. Additionally, the project will illustrate that the proposed framework is appropriate for certification of SAE L3+ automated driving functions on case studies within the project.

KT2 - Methods and tools to validate the models used in virtual validation (lifetime monitoring, residual risk, methods, and tools): The incorporation of real-world test data into the virtual V&V

process, in combination with test data derived from a knowledge base, is most likely the key to develop, certify and re-certify automated vehicles with reasonable costs and efforts. As an assessment the project will provide a knowledge base that integrates pertinent data for safety validating and testing CAVs ECA vehicles and illustrate the alimentation of a corresponding data base with pilot test data generated by the monitoring device.

KT3 - Metrics for quality assurance for ECS (mission-oriented qualification, residual risk): Standardized safety, security and privacy metrics are of high relevance for type approval, vehicle operation residual risks (e.g., insurance) and homologation procedures. As an assessment, the project will illustrate the introduced coverage metrics by application of the homologation framework on case studies within the project. The project will show on case studies in a lab demonstrator within the project, proposed techniques keeping the residual risk less than 10E-9/h.

KT4 - Definition and understanding of test coverage (residual risk, design feedback, lifetime monitoring, aggregated risk): The system understanding is the precondition to elaborate the homologation of automated vehicles. The functional safe design, system availability, and safe operation are mandatory to bring the vehicles into real traffic operation. As an assessment, the project will illustrate that the proposed processes and requirements enable to meet the expected increase of availability on case studies within the project. Virtual validation will enable to reduce the homologation effort. Reduction of fatalities which might happen during homologation only occurs in virtual environment and therefore issues are not perceived as severe as in real world driving. This increases customer acceptance.

KT5 - Methods for shorter validation in respect to acceptable residual risk (methods): The project's goal is to provide methods for shorter validation in respect to an acceptable residual risk. The project will bring together representative stakeholders from public authorities and reduce the heterogeneity of regulations to allow autonomous mode by introducing the developed homologation framework. As an assessment, the project will provide the list of propositions emanating from the project that found their way into international standards.

4 SC2 overview, structure, and demonstrators

Detecting failures at runtime is important to ensure reliability and safety by triggering an appropriate reaction, such as activating redundant components or repairing defect parts. Supply chain SC2 studies these aspects for propulsion systems, with the ambition to show the practical applicability on concrete demonstrators, illustrating that the resulting system meets reliability and safety requirements.

Supply chain SC2 is organized around four demonstrators covering various aspects of electric propulsion systems: condition monitoring and predictive maintenance of inverter power components (demonstrator 2.1), a formal methods-based monitoring device for a thermal controller (demonstrator 2.2), a health monitoring system for electric motors (demonstrator 2.3), and a secure monitoring device (demonstrator 2.4). For each of these demonstrators relies on a monitoring device to observe the current behavior of the propulsion system during operation. Supply chain SC2 also aims at methods and techniques for quality insurance, by studying evolved verification and validation techniques, including the estimation of the residual risk in presence of the investigated fault detection, localization, and repair methodologies. In particular, the risks and benefits of these additional features have to be

evaluated, to establish that as an overall effect the complete system has an acceptable residual risk and is an improvement compared to a system without these features.

The following sections present each of the four demonstrators in more detail.

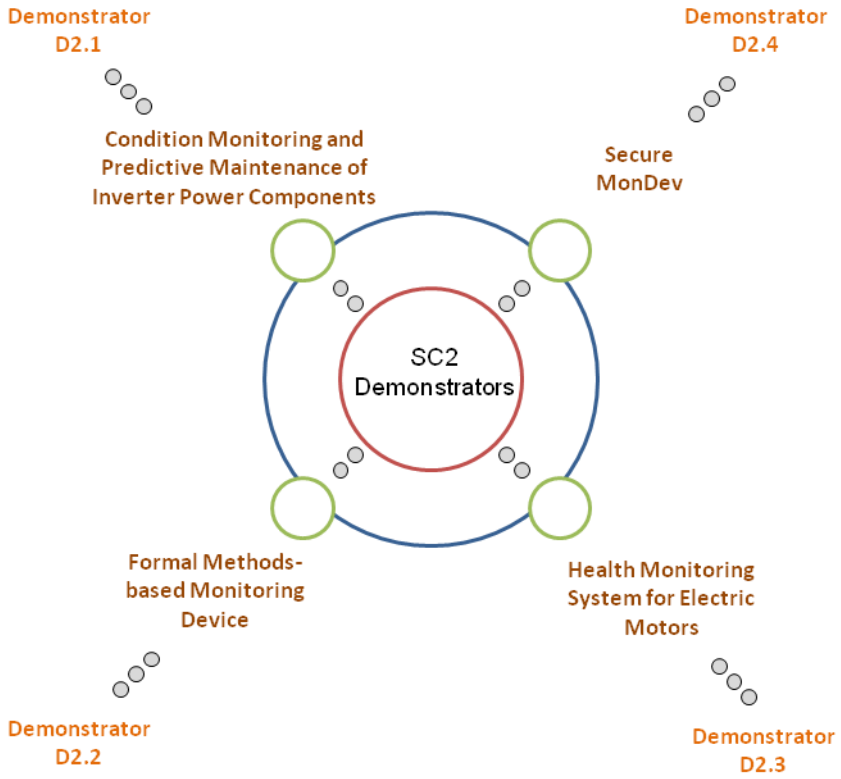

FIGURE 1: SC 2 DEMONSTRATOR STRUCTURE

5 Condition Monitoring and Predictive Maintenance of Inverter Power Components (demonstrator 2.1)

The aim of the demonstrator is to develop methods for power inverter components condition monitoring. The most critical components of the inverter are DC-link capacitors and power switching devices (IGBTs are used mostly). There exist many scientific articles regarding the condition monitoring of these devices from last two decades [Anderson et al, 2011], [Oh et al, 2015], [Sathik et al, 2016, 2018, 2019], [Tian et al, 2014], [Wuest et al, 2019], [Zhou et al, 2013], [Lee et al, 2011] and [Zhao et al, 2021]. However, none of those condition monitoring methods is used in a commercial environment like a technical standard. The reasons are additional costs related to the implementation of the methods, technical obstacles and weak robustness of these methods as well. On the other hand, the health monitoring and failure prognosis help avoiding critical malfunction of technical systems and allow planning early and cost-effective maintenance without unintended stoppage of the system. The prognosis and health management (PHM) can be understood as a first stage of covering the risk of function loss in the technical system.

5.1 Target goals and achievements

The proofing of possibilities of condition monitoring implementation for the power inverters is a goal of demonstrator 2.1. The lifetime and failures prognosis of the IGBTs and DC-link capacitors are in the scope. Typical faults for these components are following:

IGBTs

- die soldering degradation,
- bond wire corruption/lift-off,
- driver faults (insufficient driving).

DC-link capacitors

- increasing ESR,
- increasing leak current.

Methods for power inverters predictive maintenance will be key outcomes of demonstrator 2.1. Finding robust and implementable methods for power inverters component failures prediction is assumed like a good achievement. The demonstrator outcomes will contribute to new inverter architectures. The architecture includes additional HW for data acquisition and data storage in the inverter and data processing methods at the SW level.

Reliable condition monitoring and predictive maintenance can cover significant part of risks of unexpected failures and can prevent unexpected vehicle stops.

5.2 Demonstrator structure

The demonstrator structure is shown in the . Two branches of experiments will be prepared for IGBTs faults prediction and for DC-links faults prediction. Both branches will be carried out by BUT. The IFAT will eventually provide some data gathered in their own experiments and lifetime tests. These data could be used for the verification of developed methods.

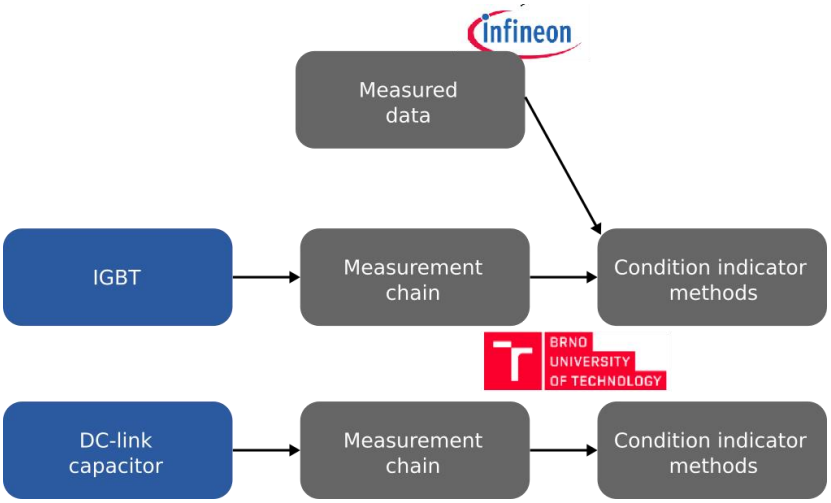

FIGURE 2: DEMONSTRATOR 2.1 STRUCTURE

Demonstrator 2.1	
	Condition Monitoring and Predictive Maintenance of Inverter Power Components (CM-IPC)
What	**What is developed in the demonstrator:** • Methods for IGBT modules and DC-link capacitors condition monitoring and predictive maintenance based on datasets analysis. • An experimental stands for accelerated ageing/fault insertion and data collection for power IGBT modules and DC-link capacitors. • Datasets of specified quantities histories during accelerated tests. • Proposal of new inverter HW architectures implementing.
How	**How the demonstrator is designed and implemented:** • Building a stand for accelerated tests and data collection of IGBT modules and DC-Link capacitors. • Multiple tests performing until component failure occurs and datasets collection. Tests with various kinds of stresses to propagate various wears/faults. • Datasets analysis, features extraction methods and remaining useful life (RUL) estimation methods development. • Verification, validation and testing according to functional and non-functional requirements defined (KPIs, measures).
Why	**Why is the demonstrator relevant and why the approach and technologies used were chosen**: • Covering of power inverter subsystem failures risks by performing early and effective diagnostics and maintenance. • The condition monitoring of power inverters can be assumed like a basic stage for covering risks of subsystem unavailability or function loss besides failure mode operation strategies.
Results (FRs)	**Demonstrator results:** • Methods and architectures for power inverters with condition monitoring capability. • Increased availability of power inverter subsystems in mission critical application by RUL prediction. • Contribution to risk management strategies and robust design of autonomous vehicles.
SC 2	Failure modes, fault detection and residual risk for safety and security in actuators and propulsion systems

5.3 Demonstrator description

A laboratory test bench for accelerated ageing of IGBTs will be built like a demonstrator. The key functionalities of the stand are the ability to control the IGBT load/stress and the ability to acquire and store records of external quantities during switching processes. It is expected to use LabVIEW development environment and NI Compact RIO platform to realize these real-time functionalities. Offline tasks related to data analysis, condition indicator development, prognosis methods development and their validation will be realized on another computer under the MATLAB environment. The demonstrator test bench structure is shown in Figure 3: Demonstrator 2.1 overview – test bench for IGBT accelerated ageingFigure 3.

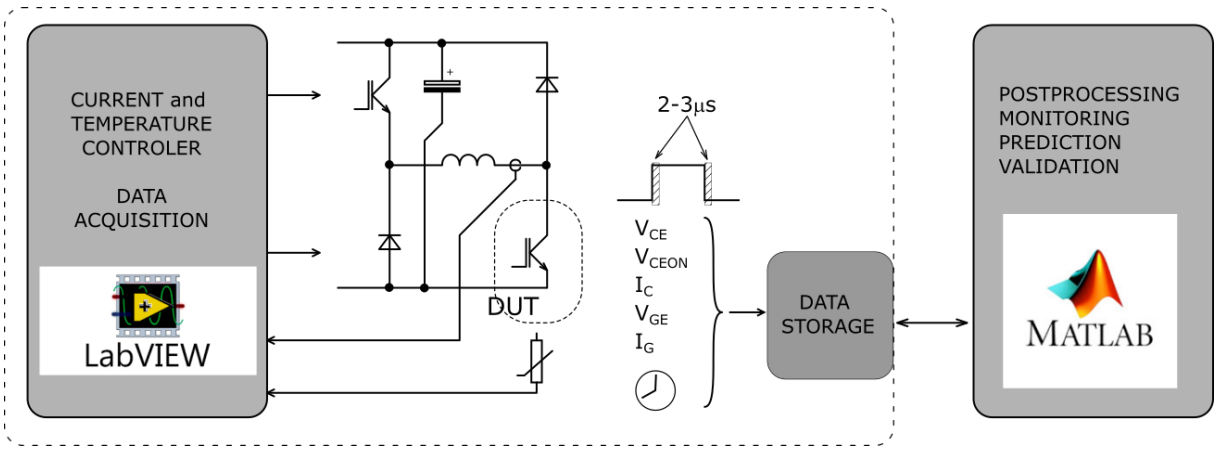

FIGURE 3: DEMONSTRATOR 2.1 OVERVIEW – TEST BENCH FOR IGBT ACCELERATED AGEING

5.4 Residual risks

Condition Monitoring (CM) & Predictive Maintenance (PM) tasks are early service actions for monitored system prior to a system fault. CM & PM can be understood as a risk control measure related to worn-out system components. One of the power transferring components in e-vehicles is the power inverter feeding traction motor. The condition monitoring of the power inverter components is not usual in commercial applications. However, it could be meaningful in case of autonomous vehicles, where very high reliability and low residual risks are required. In this demonstrator, BUT focuses on possibilities of condition monitoring of IGBTs and DC link capacitors in the power inverter.

From the definition, the risk is the composite of the predicted probability (or likelihood) and severity of each possible consequence. Power transistor/module failure is actually not monitored, and it is left as residual risk. The severity of the inverter (power train) malfunction will become more stringent with reaching higher SAE levels of autonomous cars. The planned CM & PM can reduce actual residual risk by regular or even online monitoring. The mitigation strategy in this case is the avoidance. The operation is planned to be cancelled or avoided (maintenance planned) because the safety risk exceeds a specified threshold. In the end, the CM & PM result in lower residual risk.

5.5 Demonstrator relations to the main objectives and key targets

Demonstrator 2.1 is related to following project objectives and key targets:

5.5.1 Objectives

O1 - Continuous robust design optimization for each part in the ECS value chain

Predictive maintenance helps to prevent critical faults during vehicle operation. It contributes to the robust design.

O5 - Zero emissions, zero crashes, zero congestions by ECA2030-car

Predictive maintenance helps prevent critical faults during vehicle operation. It contributes to zero congestions.

5.5.2 Key targets

KT1 - Architectures, components, sub-systems enabling virtual development and validation (monitoring device, failure risk):

The demonstrator will contribute to novel architectures of power inverters. The power device condition monitoring capability will be proposed. The additional sensing hw, data processing hw and monitoring methods will be proposed.

KT3 - Metrics for quality assurance for ECS (mission-oriented qualification, residual risk):

The condition monitoring of power inverters can be assumed like a basic stage for covering risks of system unavailability or function loss besides failure mode operation strategies.

KT4 - Definition and understanding of test coverage (residual risk, design feedback, lifetime monitoring, aggregated risk):

The basic task of condition monitoring is to provide information of the remaining lifetime for the monitored subsystem and its availability for a mission. It helps planning scenarios of vehicle utilization

and its maintenance as well. The demonstrator will contribute to adding these functionalities to power inverters.

5.6 Homologation framework mapping

Reliable predictive maintenance helps prevent system failures and contributes to lowering residual risks of the whole system. Low residual risk of failures is a criterion considered during the homologation process.

Implementation of predictive maintenance should not affect other system functionalities. The predictive maintenance task is providing demands on early maintenance.

5.7 Non-functional requirements, KPIs, and measures

We identified two main NFRs, with their KPIs and measures for demonstrator 2.1, described in Table 2 and **Error! Reference source not found.**, respectively.

TABLE 2: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 – IMPLEMENTABILITY

NFR	Implementability
NFR definition	Reasonable complexity and costs of IGBT and DC link capacitor condition monitoring for final applications.
KPI name	Implementation costs.
Description	Implementability of the data acquisition measurements (high-speed data acquisition on the IGBT potential, insulated data transfer to the inverter controller side). New architectures of the inverter system are supposed. High demands on measurement channels are assumed in the experimental test bench, however, the methods for real implementation need to be simplified as much as possible. The commercial implementation is not planned in the project. The reliable condition indicator proposal for IGBT wears will be perceived as a good result, however, reasonable complexity and costs of IGBT and DC link capacitor condition monitoring for final applications in relation to coverage failure risk must be respected.
Measure	Optimization of diagnostic algorithms.
Type of measure	Mathematical optimization, HW optimization.
Method of collection and measurement	Utilization of rapid prototyping tools with the help of advanced software for technical computing.
Demonstrator target	To find the balance between the computational and hw complexity while still achieving reliable fault prognosis.
KPI for Verification and validation	Design study, cost analysis.

TABLE 3: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 - SCALABILITY

NFR	Scalability
NFR definition	Condition indicator should be scalable for various inverter sizes, voltages, and current levels.
KPI name	Scalability to various inverter sizes.
Description	Condition indicator should be scalable for various inverter sizes, voltages, and current levels. Model based methods will be considered as an ideal approach. Finding appropriate models for degradation processes is challenging.
Measure	Design and development of condition indicator computation methods with respect to generalization and transferability.
Type of measure	Functional test with different IGBTs and different DC-link capacitors.
Method of collection and measurement	Utilization of rapid prototyping tools with the help of advanced software for technical computing.
Demonstrator target	Parameterization of condition indicators computation for broader exploitation.
KPI for Verification and validation	Functionality on various IGBT/DC-link capacitors sizes/types.

5.8 Functional requirements, KPIs, and measures

We identified four main FRs, with their KPIs and measures for demonstrator 2.1, described in Table 4, Table 5, **Error! Reference source not found.**, and Table 7, respectively.

TABLE 4: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 - DATA ACQUISITION AND STORAGE OF IGBTS TEST-BENCH QUANTITIES

FR	Data Acquisition and Storage of IGBTs test-bench quantities
FR definition	Signals on the IGBT (VCE, VCEON, VGE, IG, IC) during switching-on and switching-off processes are considered as the most critical data for further analysis and condition indicators extraction. Data for DC-link capacitors monitoring are not specified yet.
KPI name	Availability of measured data.
Description	Signals on the IGBT (VCE, VCEON, VGE, IG, IC) during switching-on and switching-off processes are considered as the most critical data for further analysis and condition indicators extraction. The demonstrator test bench should be equipped with measuring cards with sufficient sampling rates (100 MSPS is assumed) and with synchronization capability to the driver control signal.
Measure	Selection of suitable NI Compact RIO input modules, preparing the program in FPGA module to guarantee precise synchronization.

Type of measure	Measurement on an experimental setup.
Method of collection and measurement	Usage of rapid prototyping platforms (NI Compact RIO) control and measurement at the test bench in connection with high-capacity data storage. Requirements for test bench control will arise from the development work.
Demonstrator target	5 analog channels with 16 bit resolution, selectable range, 100 MSPS, sync capability to external/internal signal.
KPI for Verification and validation	Availability of defined data records at the storage device with required parameters (sampling rate, record length, timestamp).

TABLE 5: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 - DATA ACQUISITION AND STORAGE OF DC LINK CAPACITORS TEST BENCH QUANTITIES

FR	Data Acquisition and Storage of DC link capacitors test bench quantities
FR definition	The AC component of DC-link voltage and capacitor temperature are considered as the most critical data for further analysis and condition indicators extraction.
KPI name	Availability of measured data.
Description	The AC component of DC-link voltage and capacitor temperature are considered like most critical data for further analysis and condition indicators extraction. The demonstrator test bench will be equipped with measuring cards with sufficient sampling rates (1 MSPS or more should be considered).
Measure	Selection of suitable NI Compact RIO input modules, preparing the program in FPGA module to guarantee precise synchronization.
Type of measure	Verification on experimental setup.
Method of collection and measurement	Usage of rapid prototyping platforms (NI Compact RIO) control and measurement at the test bench in connection with high-capacity data storage. Requirements for test bench control will arise from the development work.
Demonstrator target	2 analog channels 16 bit, 1MSPS, sync capability to external/internal signal.
KPI for Verification and validation	Availability of defined data records at the storage device with required parameters (sampling rate, record length, time stamp).

TABLE 6: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 - MONITORING

FR	Condition indicators development and monitoring
FR definition	The demonstrator test bench must be able to process the collected data and calculate condition indicators.

KPI name	Availability of high-level data processing system.
Description	The demonstrator test bench must be able to process the collected data. Offline postprocessing on the raw data is supposed in case of the demonstrator. Custom MATLAB application running on standard PC is supposed for data processing. The condition indicator methods design, development and validation will be the main outcome of SCC2.1.
Measure	The usage of a scientific programming environment (MATLAB) for condition indicator method development, AI methods for data analysis.
Type of measure	Experiment setup, usage of appropriate tools.
Method of collection and measurement	Checking whether condition indicators output develops monotonously with the fault progress.
Demonstrator target	Defined suitable condition indicators for IGBT and DC-link capacitor health monitoring.
KPI for Verification and validation	Trending condition indicator(s) for specific fault is(are) found.

TABLE 7: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.1 - RUL PROGNOSIS

FR	RUL prognosis
FR definition	Ability to prognose monitored faults with reasonable prediction period. Reasonable prediction period is meant like sufficient time range to make acceptable preventive actions leading to avoiding the fault.
KPI name	Trustworthy Remaining Useful Life (RUL) prognosis.
Description	Failures must be predicted with a sufficient advance period to give the car a chance to plan the repair and with sufficient confidence to prevent faulty alarms and the risks and increased costs related to it.
Measure	Reliable condition indicator finding/development, appropriate RUL estimation methods application/development.
Type of measure	AI methods for data analysis, utilization of rapid prototyping tools with the help of advanced software for technical computing.
Method of collection and measurement	Verification of estimated RUL with accelerated tests records.
Demonstrator target	Meaningful RUL prognosis is in hours or more.
KPI for Verification and validation	Estimated RUL corresponds to the real RUL of the component on experimental data.

5.9 Mapping to existing standards

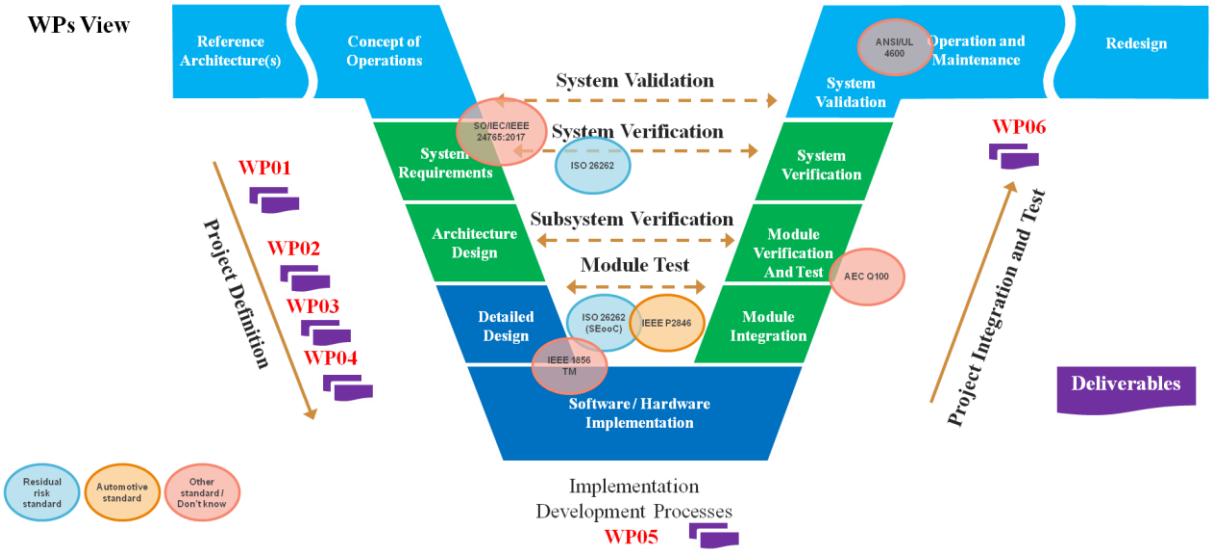

FIGURE 4: DEMONSTRATOR 2.1 - STANDARDS MAPPING V-MODEL ARCHITECTECA2030

TABLE 8: MAPPING OF EXISTING STANDARDS FOR DEMONSTRATOR 2.1

Standard code	Standard title	Why relevant	How to use
ISO 26262	Road vehicles - Functional safety	Address safety-related systems that include one or more E/E systems and that are installed in series production passenger cars (with a maximum gross vehicle mass up to 3 500 kg).	The integration of the designed predictive maintenance system and faulty prognosis should not influence the safety of the powertrain.
ANSI/UL 4600 (2020)	Standard for Evaluation of Autonomous Products	Address safety principles and processes for evaluating fully autonomous products requiring no human driver supervision.	Will be considered for 2.1 predictive maintenance methods evaluation.
IEEE P2846	Assumptions for Models in Safety-Related Automated Vehicle Behavior, (PAR approval September 2020).	Formal Model for Safety Considerations in Automated Vehicle Decision Making.	Inputs for standard update. The standard should consider predictive maintenance requests and include strategies for service actions performing.
AEC Q100	Failure mechanism based stress test qualification for integrated circuits,	AEC Q100 covers failure mechanism-based stress tests, minimum stress test driven qualification requirements and test conditions for qualifying Integrated Circuits (ICs).	Failure mechanisms description can help to build model-based methods for condition monitoring and predictive

	(Rev-H, September 2014).	The idea is to determine devices which can pass the defined stress tests, and provide devices which can offer certain level of quality and reliability in the application. • AEC Q100 defines four temperature ranges based on the operating range of ICs.	maintenance. Related standards AEC Q101, AEC Q200 can be also utilized in demonstrator 2.1.
ISO/IEC/IEEE 25765:2017	Systems and software engineering - Vocabulary	Provides a common vocabulary applicable to all systems and software engineering work, and includes references to the active source standards for definitions so that systems and software engineering concepts and requirements can be further explored.	Will be considered like a general standard.
IEEE Std 1856TM-2017	IEEE Standard Framework for Prognostics and Health Management of Electronic Systems	It covers all aspects of PHM of electronic systems, including definitions, approaches, algorithms, sensors and sensor selection, data collection, storage and analysis, anomaly detection, diagnosis, decision and response effectiveness, metrics, life cycle cost of implementation, return on investment, and documentation.	Will be optionally used like a guideline for requirement definition and development steps in the lifecycle process.

5.10 Verification and validation

A test bench for components will be built for test purposes. The methods for condition monitoring and prognosis will be validated on data gathered during accelerated tests of multiple samples of tested devices.

5.11 Demonstrator milestones

The milestones of demonstrator 2.1 are linked with the planned deliverables in tasks where the work is being conducted, as illustrated in Figure 5.

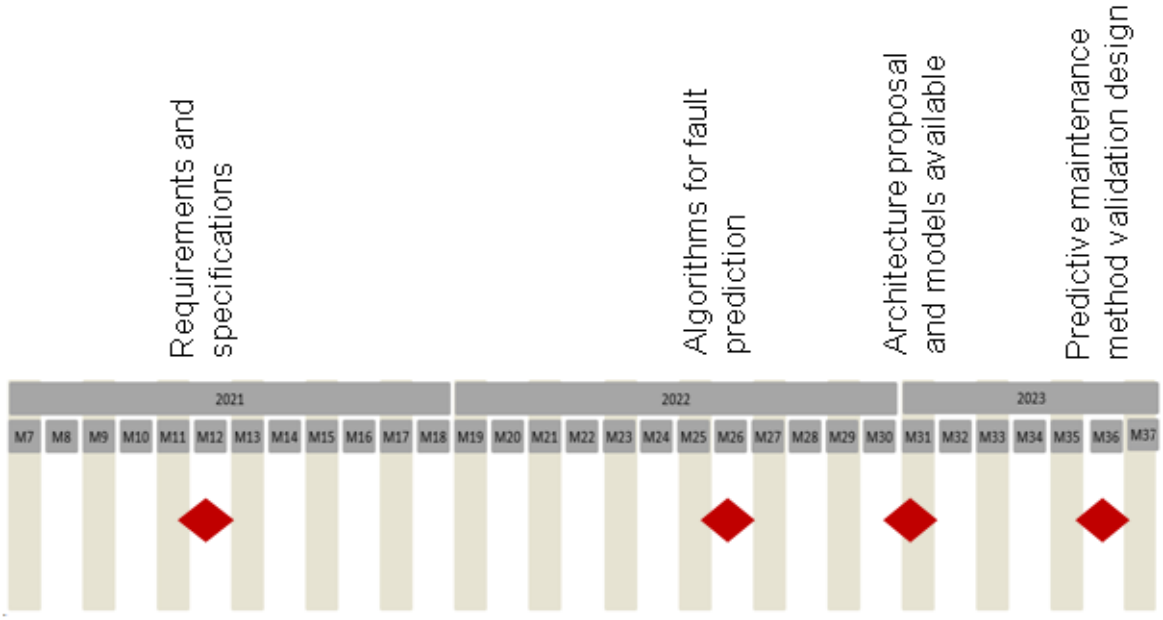

FIGURE 5: DEMONSTRATOR 2.1 MILESTONES TIMELINE

6 Formal Methods-based Monitoring Device (demonstrator 2.2)

This demonstrator, proposed by AVL and including contributions from TUG and INRIA, will focus on using formal methods, such as model-based fault localization, as well as failure models, as a Monitoring Device.

6.1 Target goals and achievements

The demonstrator should be able to validate the methods developed by AVL, TUG and INRIA. For this a co-simulation will be used. It will use the method's outputs to simulate a thermal controller (embedded in a vehicle and environment simulation). The thermal controller's output will be the basis for the residual risk assessment, model-based fault localization and residual risk quantification. The developed methods should be applicable to the real world; However, because of testability, availability, and safety concerns a simulation was chosen to demonstrate them.

6.2 Demonstrator structure

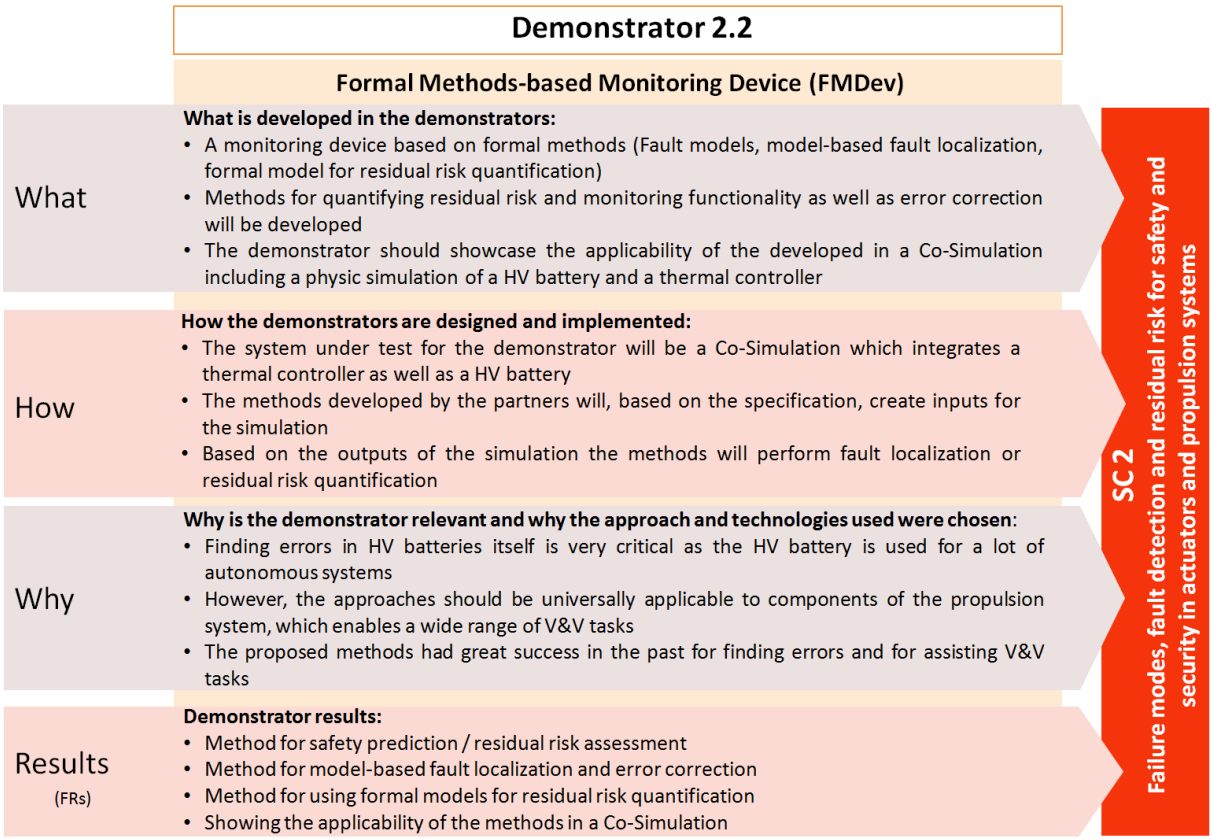

FIGURE 6: DEMONSTRATOR 2.2 STRUCTURE

6.3 Demonstrator description

The demonstrator will consist of multiple parts, where each partner will contribute to a formal-method-based Monitoring Device:

- **Co-Simulation**: This part was already developed. It will accept simulation parameters and expose measurements that are needed for the formal methods considered. The main SUT (system under test) will be a thermal controller for which a specification is available.
- **Safety Prediction / Residual Risk Assessment**: AVL will contribute a method to indicate the safety status of the SUT and provide a residual risk assessment for it.
- **Model-Based Fault localization and Error Correction**: TUG will contribute a method for fault localization, detection and error correction in the SUT.
- **Formal Models for Residual Risk Quantification**: INRIA will contribute a method that exploits the SUT's formal model for diagnosis and residual risk quantification. The method will take advantage of the CADP toolbox [Garavel et al, 2013] and recent work on fault-localization [Hofer et al, 2018], test-case generation [Marsso et al, 2018], and quantitative analysis [Mateescu et al, 2018].

Figure 7 gives a block diagram of the demonstrator, showing the core building blocks including the partner roles.

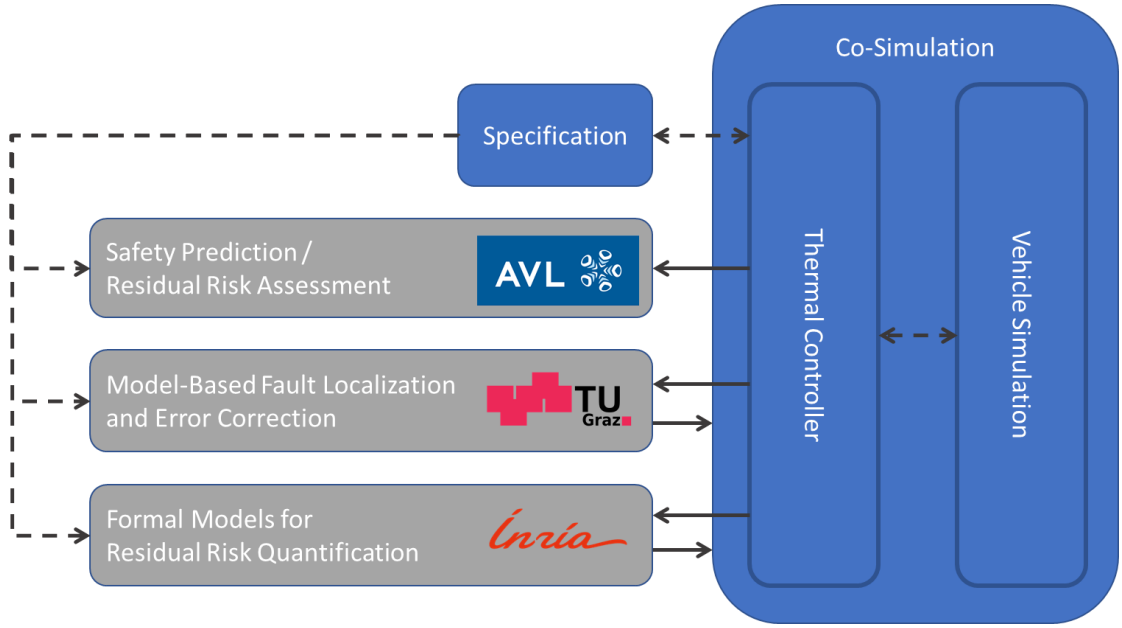

FIGURE 7: DEMONSTRATOR 2.2 OVERVIEW

6.4 Residual risks

According to the ISO 26262 standard, the notion of risk is a combination of probability and severity of a failure. Two types of risks can be distinguished: *inherent* risks are those associated with the worst foreseeable situation, whereas *residual* risks take into account the effect of the safety actions, which aim at bringing the risk down to an acceptable level.

Monitoring a system can be part of a risk control and avoidance strategy, since it contributes to reduce the residual risks by enabling to initiate a maintenance action before the actual risk happens.

6.5 Demonstrator relations to the main objectives and key targets

The demonstrator promotes the usage of formal methods to assess the operation of the Monitoring Device in a validation context, and therefore it is related to the objectives and key targets oriented to validation and robust design.

6.5.1 Objectives

O1 - Continuous robust design optimization for each part in the ECS value chain (Technical): A monitoring device based on formal methods can enhance the robustness of components in the ECS value chain.

O2 - Framework for safety validation of ECS value chain (Technical): The demonstrator will show how the Monitoring Device could be used in a validation framework. The Thermal-Controller provided by AVL will simulate a SUT, for which safety relevant metrics can be extracted.

O3 - Identification and management of residual risks over the entire ECS value chain (Technical): Especially the contribution from AVL “Safety Prediction / Residual Risk Assessment” and from INRIA “Formal Models for Residual Risk Quantification” will tackle this objective.

O4 - End-user acceptance by trustworthy ECS value chain (Value): Basing the Monitoring Device on formal methods enables us to reason about the Monitoring Device. This will hopefully help with the end-user acceptance.

O5 - Zero emissions, crashes, and congestions by ECA2030 vehicle (Value): The goal of the Monitoring Device is to warn the system before a crash happens. Reaction to this crash will lead to a reduction of crashes, which brings us a step closer to the goal of zero crashes.

6.5.2 Key targets

KT1 - Architectures, components, sub-systems enabling virtual development and validation (monitoring device, failure risk): The demonstrator consists of a Co-Simulation of a Thermal-Controller, and a similar setup can be used for other components, sub-systems, or the whole vehicle. This enables a wide range of application for virtual development and validation.
KT2 - Methods and tools to validate the models used in virtual validation (lifetime monitoring, residual risk, methods, and tools): The contribution from the partners will be used to virtually validate a model of a Thermal-Controller.
KT3 - Metrics for quality assurance for ECS (mission-oriented qualification, residual risk): The definition of the residual risk, its assessment, and quantification will be important quality assurance metrics that will be used in our demonstrator.
KT4 - Definition and understanding of test coverage (residual risk, design feedback, lifetime monitoring, aggregated risk): AVL's system analysis will provide a usage space analysis for the Thermal-Controller.
KT5 - Methods for shorter validation in respect to acceptable residual risk (methods): Because of the usage of virtual validation instead of real-world validation, testing time can be reduced.

6.6 Homologation framework mapping

The Monitoring Device should notify a higher decision system of possible errors. This decreases the residual risk because the higher decision system can react to faults that (i) potentially will occur in the future and (ii) faults that it would have otherwise missed.

Furthermore, we will also investigate small error correction methods. Either this error correction methods could provide an "emergency" behaviour that is executed until the higher decision system can react to the fault or a recommendation to the higher decision system.

6.7 Non-functional requirements, KPIs, and measures

We identified six most relevant NFRs, KPIs and Measures for demonstrator 2.2. In Table 9, Table 10, and Table 11 we present the three NFRs related to the failure model, and in Table 12, Table 13, and Table 14 we present the three NFRs related to the diagnosis aspects of demonstrator 2.2.

TABLE 9: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - RELIABILITY

NFR	Reliability
NFR definition	The failure model has to be more reliable than the SUT.
KPI name	Divergence of failure model and SUT
Description	The fault model has to be validated against multiple usage cycles to ensure that the failure mode is more reliable than the SUT.
Measure	Divergence between the failure model and different usage cycles.

Type of measure	Degeneration of the battery.
Method of collection and measurement	Measurements performed on a battery.
Demonstrator target	
KPI for Verification and validation	The divergence between the failure model and usage cycles has to be under a certain threshold.

TABLE 10: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - PERFORMANCE OF FAILURE MODEL

NFR	Performance of failure model
NFR definition	The failure model has to be able to calculate the degeneration of the battery in real-time.
KPI name	Latency
Description	Because we want to calculate the degeneration of the battery during operation and notify the user about potential failure, the failure model must also be real-time capable.
Measure	Latency of the failure mode.
Type of measure	Time
Method of collection and measurement	Measuring timing of the failure mode.
Demonstrator target	
KPI for Verification and validation	The latency of the failure model has to be near zero.

TABLE 11: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - AVAILABILITY

NFR	Availability
NFR definition	The battery of the SUT needs to provide fast enough measurements such that the failure model can calculate the degeneration of the battery.
KPI name	Availability of measurement data.
Description	The measurement data of the battery has to be provided fast enough for the failure model to calculate the degeneration of the battery.
Measure	Measurement results per timestep.
Type of measure	Events/time
Method of collection and measurement	Measure how many measurements per timestep the battery can provide.
Demonstrator target	
KPI for Verification and validation	The measurement frequency must be high enough for the failure model to work.

TABLE 12: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - PERFORMANCE OF DIAGNOSIS

NFR	Performance of diagnosis
NFR definition	Real time online diagnosis.
KPI name	
Description	Faults have to be detected and diagnosed in a real time manner. The available sensors and interfaces have to allow for real time analysis.
Measure	Latency.
Type of measure	
Method of collection and measurement	Latency measures performed on demonstrator using generated test suite, as well as re-tested on target hardware and system.

Demonstrator target KPI for Verification and validation	Latency.

TABLE 13: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - ROBUSTNESS

NFR	Robustness
NFR definition	The diagnostic model should be robust to noise, sensor deviations, and sensor failures.
KPI name	
Description	The model takes varying accuracy, precision, and uncertainties of inputs resulting deviations into consideration. The model must remain operational (possibly with reduced capabilities) in case of a sensor failure.
Measure	Reduction of KPIs as defined for functional requirements. (Model coverage and classification error.)
Type of measure	
Method of collection and measurement	Using the test suite generated for FR Fault diagnosis and additional injection of noise and sensor failures.
Demonstrator target	
KPI for Verification and validation	Reduction of KPIs as defined for functional requirements. (Model coverage and classification error.)

TABLE 14: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - TESTABILITY

NFR	Testability
NFR definition	Diagnostic models testability.
KPI name	
Description	The models diagnostic capabilities are to be tested using the demonstrator model. The diagnostic model is tested on a big number injection generated test cases, as well as test scenarios deduced from the demonstrators specification (e.g., known industrial test bed scenarios) and test scenarios deduced from real world driving contexts.
Measure	Model coverage, Fault coverage, Multi-fault coverage.
Type of measure	
Method of collection and measurement	Automated testing using above described generated test suites.
Demonstrator target	
KPI for Verification and validation	Model coverage, Fault coverage, Multi-fault coverage.

6.8 Functional requirements, KPIs, and measures

We identified six most relevant FRs, KPIs and Measures for demonstrator 2.2. In Table 15, Table 16, and Table 17 we present the three FRs related to the failure model, and in Table 18, Table 19, and Table 20 we present the three FRs related to the diagnosis aspects of demonstrator 2.2.

TABLE 15: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - MONITORING

FR	Monitoring
FR definition	The failure model gives a prediction of the remaining life and, therefore, residual risk of the battery.

KPI name	Monitoring of battery
Description	To enable the main monitoring functionality of the failure model, the failure model has to give the user feedback about the remaining lifetime of the battery. Therefore, a requirement is that the failure model gives this feedback.
Measure	Functional test
Type of measure	Functional test
Method of collection and measurement	Functional tests
Demonstrator target	
KPI for Verification and validation	Enough tests should be performed to have confidence that the failure model provides the user feedback about the remaining lifetime of the battery.

TABLE 16: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - COMPATIBILITY

FR	Compatibility
FR definition	The failure model should be compatible with other Monitoring Devices.
KPI name	Compatibility with other Monitoring Devices
Description	To ensure that the fault model is compatible with other Monitoring Devices, the fault model should not change any measurement data and not manipulate any other data.
Measure	Functional test
Type of measure	Functional test
Method of collection and measurement	Functional tests
Demonstrator target	
KPI for Verification and validation	Enough tests should be performed to have confidence that the failure model does not change the measurement data or any other data in the system.

TABLE 17: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - FUNCTIONAL COMPLETENESS

FR	Functional completeness
FR definition	The failure model should be correct in the predefined usage space.
KPI name	Functional completeness w.r.t. The defined usage space.
Description	The failure model should operate correctly in the defined usage space. Outside the defined usage space, the behavior of the failure model is not specified.
Measure	Functional test
Type of measure	Functional test
Method of collection and measurement	Functional tests
Demonstrator target	
KPI for Verification and validation	Enough tests should be performed to have confidence that the failure model behaves correctly in the predefined usage space.

TABLE 18: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - FAULT DIAGNOSIS

FR	Fault diagnosis
FR definition	Model-based diagnosis for fault localization.
KPI name	Model coverage and classification error.
Description	The diagnostic model offers fault isolation and identification capabilities for single and multi-fault scenarious.

	Intermittent and incipient faults are to be considered, as well as diagnosis of novel faults. (Novel in the sense of unanticipated at the time of model creation)
Measure	Fault coverage and classification error.
Type of measure	
Method of collection and measurement	Injecting faults into demonstrator to generate a test suite of faults. The diagnostic model is tested against this suite to measure coverage and classification errors (precision and recall).
Demonstrator target	
KPI for Verification and validation	Model coverage and classification error.

TABLE 19: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - DIAGNOSIS ERROR ESTIMATES

FR	Diagnosis error estimate
FR definition	Runtime diagnosis error estimates.
KPI name	Model coverage and classification error.
Description	The diagnostic model provides an estimate of classification error for each diagnosis, based on the state of the model and demonstrator.
Measure	Estimate error.
Type of measure	
Method of collection and measurement	Using the test suite generated for FR Fault diagnosis.
Demonstrator target	
KPI for Verification and validation	Estimate error.

TABLE 20: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.2 - FAULT CORRECTION

FR	Correction/Reaction to fault diagnosis
FR definition	Correction and reaction to diagnosed faults.
KPI name	
Description	For a diagnosed fault the system provides an adequate actionable strategy to either correct or mitigate the fault. The provided strategy has to minimize the resulting risk of damages and risk to passengers.
Measure	Model coverage and classification error.
Type of measure	
Method of collection and measurement	Using the test suite generated for FR Fault diagnosis. Evaluation of the selected strategy on demonstrator.
Demonstrator target	
KPI for Verification and validation	Model coverage and classification error.

6.9 Mapping to existing standards

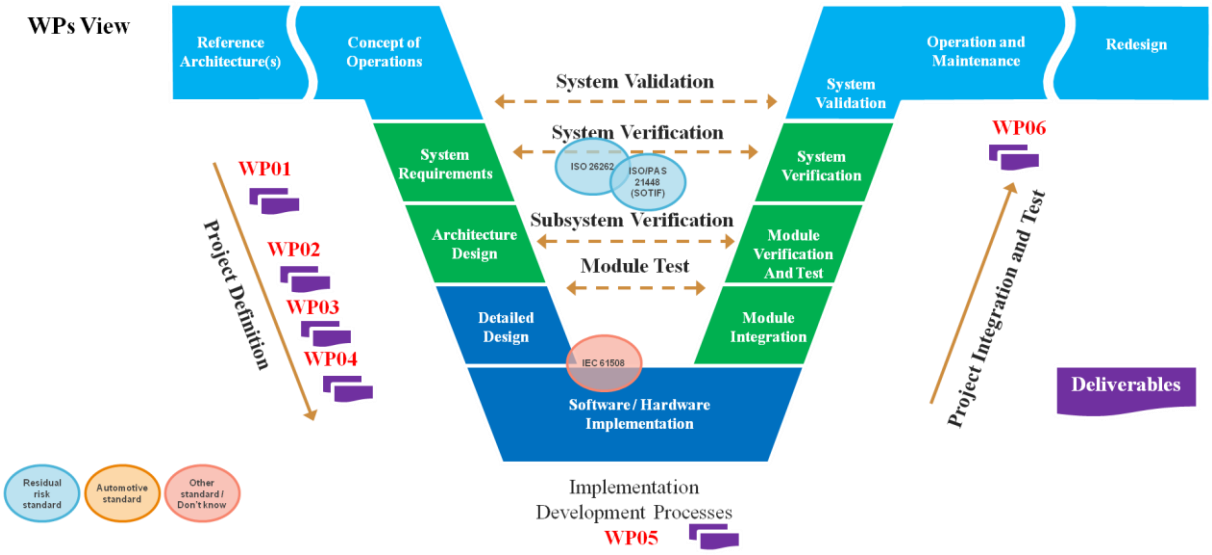

FIGURE 8: DEMONSTRATOR 2.2 - STANDARDS MAPPING V-MODEL ARCHITECTECA2030

TABLE 21: MAPPING OF EXISTING STANDARDS FOR DEMONSTRATOR 2.2

Standard code	Standard title	Why relevant	How to use
ISO 26262	Road vehicles - Functional safety	Address safety-related systems that include one or more E/E systems and that are installed in series production passenger cars (with a maximum gross vehicle mass up to 3 500 kg).	Reference
ISO/PAS 21448:2019 (SOTIF)	Road vehicles - Safety of the intended functionality	This document provides guidance on the applicable design, verification and validation measures needed to achieve the safety of the intended functionality.	Reference
IEC 61508 (Eight parts 0-7)	Functional safety of electrical/electronic/programmable electronic safety-related systems	Address aspects to be considered when electrical/ electronic/ programmable electronic (E/E/PE) systems are used to carry out safety functions. Requirements for ensuring that systems are designed, implemented, operated, and maintained to provide the required safety integrity level (SIL).	Reference

6.10 Verification and validation

We will perform an in depth analysis of the Monitoring Device's behaviour. Because the Thermal-Controller simulation is physics based we can assume that the simulation will behave the same as a real thermal controller would. Meaning the simulation will be our ground truth.

The analysis of the behaviour will include which type of errors we could successfully detect with the different methods. Also we will compare the residual risk estimations with typical failure modes that evolve over time.

6.11 Demonstrator milestones

The following milestones are planned to be achieved, as illustrated in Figure 9.

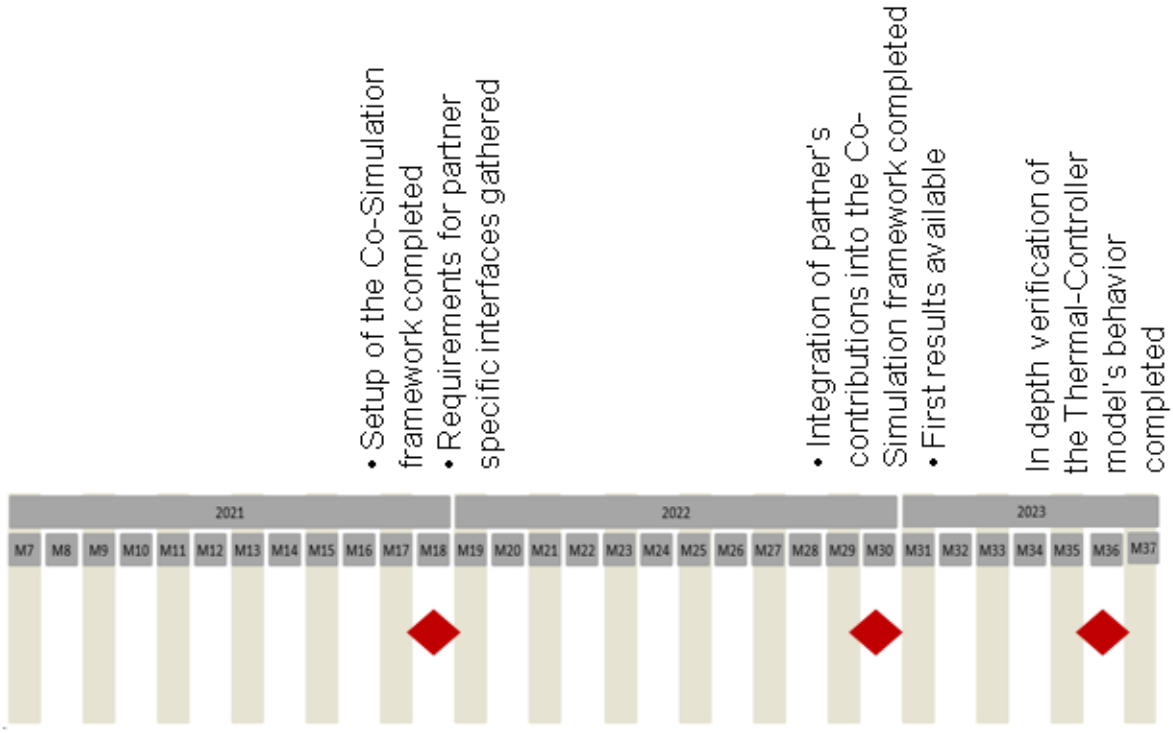

FIGURE 9: DEMONSTRATOR 2.2 MILESTONES TIMELINE

7 Health Monitoring System for Electric Motors (demonstrator 2.3)

Electric motors have the potential to become the main drive variant used in the next few years and thus also in the next generations of vehicles. As vehicles become increasingly automated, the complexity of the individual components and their mutual interactions continues to increase, and users' understanding of the technology in the vehicle diminishes. This can also lead to a loss of user confidence and acceptance towards the new technologies. Monitoring of individual components and the entire vehicle during operation can help to detect possible faults at an early stage, which could otherwise lead to defects and, as a result, accidents. In addition, the monitoring can be used to provide the user with recommendations for preventive maintenance work. This in turn can reduce the number of accidents in practice and strengthen user confidence.

In the scientific work of recent years, the condition monitoring of motors has been given a high importance as an essential technique towards a reliable and safe operation in critical processes. [Luo et al, 2019], [Nitish et al, 2019], and [Liang et al, 2020] give an overview of the current state of the art in this field. More and more authors, e.g. [Holbert et al, 2006], [Liu et al, 2019], and [Stief et al, 2019], propose a combination of measurement data to improve the results of condition monitoring, each

representing different aspects of motor operation, such as inverter current measurements, mechanical vibration measurements, temperature measurements and magnetic flux measurements.

7.1 Target goals and achievements

The demonstrator is intended to detect mechanical stress and aging effects of the bearings caused by a change in the behavior of rotating components and to derive maintenance recommendations for the user of the vehicle. The demonstrator will be used as an example to show how mechanical forces acting in the plane of the end shield can be measured and used as indicators for imbalances of the rotor or the running unsteadiness of the engine.

In addition to the possibility of analyzing the behavior of electric motors on the inverter side using the current and voltage waveforms, this project will measure and analyze mechanical effects and provide indicators for the motor control.

7.2 Demonstrator structure

The demonstrator is an electric motor, shown on FIGURE 10, which was developed as a near-axle traction motor in the 3Ccar project. Measurements will be carried out on a motor model, i.e. a motor with an unbalance disc instead of a normal rotor, and on a real motor with an identical housing. In the 3Ccar project, sensors were integrated into the end shield, which will now be used to measure the mechanical forces.

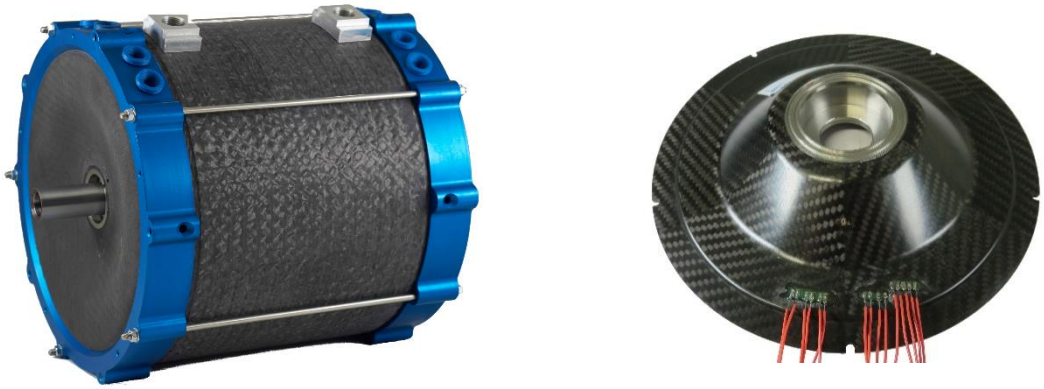

FIGURE 10: DEMONSTRATOR 2.3 STRUCTURE - LIGHT WEIGHT ELECTRIC MOTOR AND END SHIELD WITH STRUCTURALLY INTEGRATED SENSORS (SOURCE: TU DRESDEN/ILK)

The Institute of Lightweight Engineering and Polymer Technology (ILK) at TU Dresden (TUDR) will carry out the measurements on the motor model with the sensors integrated in the end shield. In addition, TUDR will simulate the influence of imbalances of the rotor. The measurements on the real engine will be performed at Vysoke Uceni Technicke v Brne (BUT). Based on this, TUDR will develop algorithms for condition indication and maintenance planning that can be executed as part of the motor control system.

7.3 Demonstrator description

The demonstrator consists of two separate and generally independent components: the motor model with the unbalance disc and the real motor. The motor model offers the advantage that different

unbalances can be directly introduced into the system and tested. Due to its structure, however, the motor model cannot be driven directly with an inverter, and requires an additional motor for this purpose. This also means that mechanical forces, which may act on the end shield and are caused by the electromagnetic field between the rotor and stator of the motor, do not occur and therefore cannot be measured.

This disadvantage of the motor model shall be compensated by measurements on the real motor. The real motor has the same casing as the motor model. Thus, the effects of the magnetic field and the unbalance disc on the end shield should be directly comparable. Both partial studies together form the basis for developing the algorithms for the condition identification and for planning preventive maintenance work.

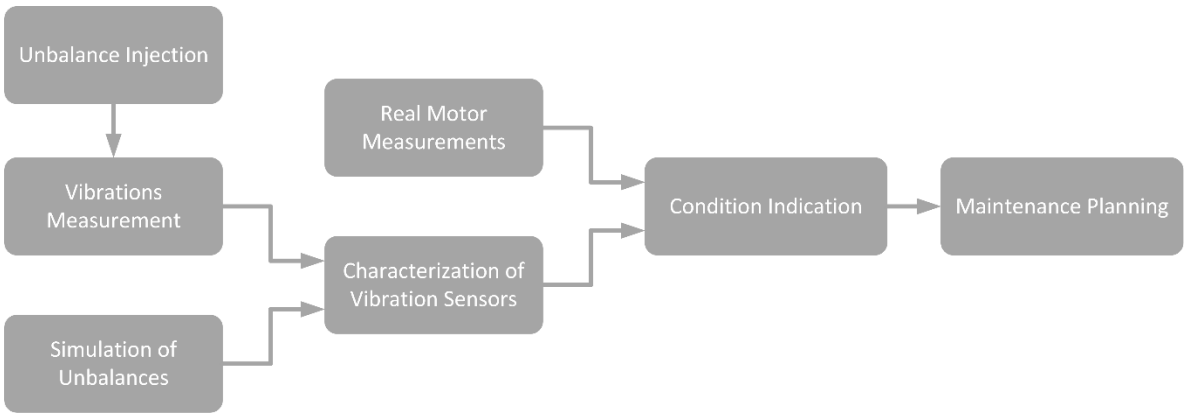

FIGURE 11: DEMONSTRATOR 2.3 OVERVIEW - WORK ITEMS AND THEIR INTERDEPENDENCIES

7.4 Residual risks

The residual risk can be understood as the result of a containment process. Starting from a basic situation with a known risk, measures can be taken to reduce this risk. In doing so, various parameters can be influenced - based on the ISO 26262 standard, for example, the probability of occurrence, the severity and the controllability of the causing event. The risk remaining after this can be seen as the residual risk.

As part of this demonstrator, TUDR aims at using statistical surveys of road traffic accidents as a basis. Given the probability of early detection of faults that can be achieved by mechanical vibration measurements, which is to be determined in the project, there is a possible reduction in the basic risk and thus the remaining residual risk. As defined in the standard ISO 26262-1:2018, residual risk is the risk that remains after safety measures have been deployed. Risk, for its part, is defined as the combination of the probability of occurrence of a harm and the severity of that harm.

It is planned to use statistical surveys as a basis for the residual risk assessment. The probability of early detection of faults that can be identified by mechanical vibration measurements, which is to be determined in the project, results in a possible reduction of the inherent risk and thus the remaining residual risk.

Potential problems with this approach may be that electric motors have not been used as drive motors in vehicles for very long and that the statistical data may not be available in the level of detail that would be necessary.

7.5 Demonstrator relations to the main objectives and key targets

The demonstrator is intended to show the measurement of the mechanical stress on the end shields of an electric motor during operation in order to derive recommendations for preventive maintenance. The objectives are therefore in the fields of avoiding accidents and improving end user acceptance.

7.5.1 Objectives

O4 – End-user acceptance by trustworthy ECS value chain (Value): Maintenance recommendations based on actual wear measurements during the operating life of the electric drive motor give the user more safety and confidence and can lead to a higher acceptance towards the technology within automated vehicles.

O5 – Zero emissions, crashes, and congestions by ECA2030 vehicle (Value): Wear measurements during the operating life of the electric drive motor make it possible to take the detected wear into account in the motor control and to replace worn components before they fail and may become the cause of an accident.

SC2-O2 – Providing methods and tools for fault detection, localization and repair: The condition monitoring of the electric drive motor during operation helps to detect potential wear and therefore the early detection of possible faults and failures. Maintenance recommendations support preventive repairs to avoid failures of the drive motor.

7.5.2 Key targets

KT2 – Methods and tools to validate the models used in virtual validation (lifetime monitoring, residual risk, methods, and tools): Observations from health monitoring performed throughout the lifetime of the electric motor can be used to verify the results of simulations of the motor's behavior.

7.6 Homologation framework mapping

The early detection of mechanically related faults and the planned recommendations for preventive maintenance of the vehicle help to reduce or avoid possible accidents caused by system failures and thus reduce the risk of using the vehicles. In addition, the information collected at runtime about the current state of the motor can be used directly in the control of the vehicle.

Both, a higher safety of the powertrain and an acceptable residual risk, are important criteria for the approval of a vehicle for public road traffic.

7.7 Non-functional requirements, KPIs, and measures

The quality of the electric motor health monitoring is determined by non-functional parameters, such as the functional appropriateness of the system and the analyzability of the measurement results. These are the two main NFRs, with their KPIs and measures, identified for demonstrator 2.3, and they are described in Table 22 and Table 23, respectively.

TABLE 22: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.3 - FUNCTIONAL APPROPRIATENESS

NFR	Functional appropriateness
NFR definition	Functional appropriateness of the monitoring system
KPI name	Degree of detectability
Description	What proportion of the injected unbalances can be detected?

Measure	Detectability of unbalances
Type of measure	Quantitative (ratio) Runtime measurements
Method of collection and measurement	$X = \frac{A}{B}$ A … Number of measurements in which unbalances can be detected B … Number of all unbalance measurements
Demonstrator target	
KPI for Verification and validation	Comparision between measurement results and simulation results

TABLE 23: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.3 - ANALYZABILITY

NFR	Analyzability
NFR definition	Analyzability of the sensor measurements
KPI name	Degree of analyzability
Description	Which influences can be detected with which sensor type?
Measure	Detectability of forces
Type of measure	Quantitative (ratio) Runtime measurements
Method of collection and measurement	$X = \frac{A}{B}$ A … Number of influences that can be detected B … Number of all influences tested
Demonstrator target	
KPI for Verification and validation	Comparison between different sensor types in time and/or frequency domain

7.8 Functional requirements, KPIs and measures

When detecting mechanical stress, the sensors should be able to detect unbalances as accurately as possible – at the same time, however, a distinction between normal stress, as it occurs when the motor is directly driven by an inverter, and stress due to wear should be made. Based on this, we identified three functional requirements, with their KPIs and measures, for demonstrator 2.3, described in Table 24, **Error! Reference source not found.**, and Table 26 respectively.

TABLE 24: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.3 - SENSOR SENSITIVITY

FR	Sensor sensitivity
FR definition	The different sensors should be able to detect the mechanical stress on the electric motor's end shields caused by unbalances.
KPI name	Degree of sensitivity
Description	How well does the specific sensor type detect the injected unbalances?
Measure	Sensor sensitivity
Type of measure	Quantitative (signal amplitude ratio) Runtime measurements
Method of collection and measurement	$X = \frac{A}{B}$ A … Output signal of the sensor with injected unbalance B … Output offset signal of the sensor without unbalance
Demonstrator target	

KPI for Verification and validation	Comparison between different sensor types in time and/or frequency domain

TABLE 25: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.3 - DIFFERENTIATION

FR	Differentiation
FR definition	Distinguishability between normal stress and wear and tear
KPI name	Degree of differentiation
Description	How well can different influences be differentiated in the measurement signals?
Measure	Distinguishability between normal stress and wear and tear
Type of measure	Quantitative (signal amplitude ratio)
Method of collection and measurement	Runtime measurements $X = \frac{A}{B}$ A … Output signal of the measurement unit with injected unbalance B … Output signal of the measurement unit when the motor is driven directly by an inverter
Demonstrator target	
KPI for Verification and validation	Comparison between direct drive and injected unbalances in time and/or frequency domain

TABLE 26: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.3 - ROBUSTNESS

FR	Robustness
FR definition	The detectable signals and derivable effects and parameters should be robustly and reliably determined and describable
KPI name	Degree of robustness
Description	How reliably can the unbalances injected into the motor be determined from the measurement signals?
Measure	Conformance of measurements to known signal patterns as described in the literature and standards
Type of measure	Qualitative
Method of collection and measurement	Test of the conformance after evaluation of the measured values
Demonstrator target	
KPI for Verification and validation	Comparison between direct drive and injected unbalances in time and/or frequency domain

7.9 Mapping to existing standards

The following standards are relevant for the measurement of mechanical vibrations at the end shield for health monitoring of electric drive motors.

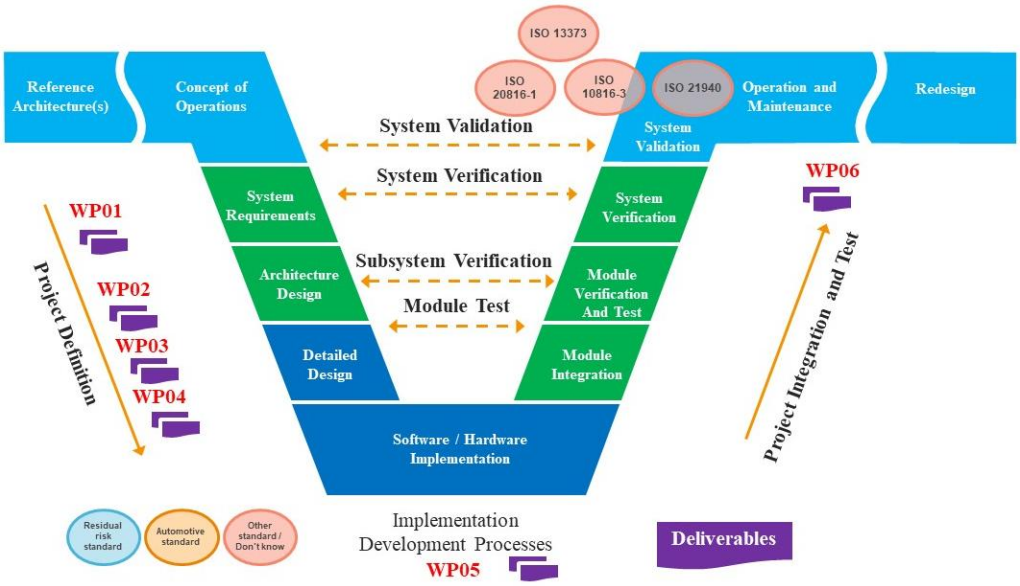

FIGURE 12: DEMONSTRATOR 2.3 - STANDARDS MAPPING V-MODEL ARCHITECTECA2030

TABLE 27: MAPPING OF EXISTING STANDARDS FOR DEMONSTRATOR 2.3

Standard code	Standard title	Why relevant	How to use
DIN ISO 10816-3:2018 ISO 10816-3:2017	Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15000 r/min when measured in situ	The criteria of this part of ISO 10816 apply to in situ broad-band vibration measurements taken on the bearings, bearing pedestals, or housing of machines under steady-state operating conditions within the nominal operating speed range. They relate to both acceptance testing and operational monitoring. The evaluation criteria are designed to apply to both continuous and non-continuous monitoring situations.	Evaluation of vibrations measured on the end shields of the electric motor
DIN ISO 13373 (parts 1, 2, 3, and 9) ISO 13373 (parts 1, 2, 3, and 9)	Condition monitoring and diagnostics of machines – Vibration condition monitoring	The principal purpose of vibration condition monitoring of machinery is to provide information on the operating condition of the machine for protection and predictive maintenance. An integral part of this process is the evaluation of the vibratory condition of the machine over operating time. In contrast to vibration testing used strictly for diagnostic or acceptance purposes, condition monitoring involves the acquisition of data which can be compared	Monitoring of vibrations measured on the end shields of the electric motor

		over a span of time, and emphasizes the changes in vibration behavior rather than any particular behavior by itself..	
DIN ISO 20816-1:2017 ISO 20816-1:2016	Mechanical vibration – Measurement and evaluation of machine vibration – Part 1: General guidelines	This standard establishes general conditions and procedures for the measurement and evaluation of vibration using measurements made on rotating, non-rotating and non-reciprocating parts of complete machines. It is applicable to measurements of both absolute and relative radial shaft vibration with regard to the monitoring of radial clearances, but excludes axial shaft vibration. The general evaluation criteria, which are presented in terms of both vibration magnitude and change of vibration, relate to both operational monitoring and acceptance testing. They have been provided primarily with regard to securing reliable, safe, long-term operation of the machine while minimizing adverse effects on associated equipment. Guidelines are also presented for setting operational limits.	Measurement and evaluation of vibrations measured on the end shields of the electric motor
DIN ISO 21940 (parts 1 and 11) ISO 21940 (parts 1, 11, and 31)	Mechanical vibration – Rotor balancing	Vibration caused by rotor unbalance is one of the most critical issues in the design and maintenance of rotating machines. It gives rise to dynamic forces which adversely affect both machine and human health and well-being. Balancing is explained in a general manner, using the specific terms and definitions, to help readers to select the appropriate balancing approach for their application. Part 11 of this standard establishes procedures and unbalance tolerances for balancing rotors with rigid behavior. It specifies (a) the magnitude of the permissible residual unbalance, (b) the necessary number of correction planes, (c) the allocation of the permissible residual unbalance to the tolerance planes, and (d) how to account for errors in the balancing process. Part 31 of this standard specifies methods for determining machine vibration sensitivity to unbalance and provides evaluation guidelines as a function of the proximity of relevant resonance rotational speeds to the	Evaluation of vibrations measured on the end shields of the electric motor caused by unbalances

		operating speed. This part of ISO 21940 is only concerned with once-per-revolution vibration caused by unbalance. It also makes recommendations on how to apply the numerical sensitivity values in some particular cases.	
ISO 26262:2018	Road vehicles – Functional safety	Address safety-related systems that include one or more E/E systems and that are installed in series production passenger cars (with a maximum gross vehicle mass up to 3500 kg).	The standard defines criteria for assessing risks and methods to ensure functional safety.

7.10 Verification and validation

The demonstrator takes into account the following two scenarios:

1. Vibrations caused by injected unbalances in a motor model driven by another machine
2. Vibration caused by the direct drive of an electric motor, which has the same housing as the motor model, with an inverter

The following methods are used to evaluate the results from the scenarios:

- Conformance of measurement results and simulation results
- Comparison of the capabilities of different sensor types
- Comparison of the output parameters of the measuring system under different influences, such as operation with and without injected unbalances as well as direct drive with an inverter

7.11 Demonstrator milestones

The following milestones are planned to be achieved for demonstrator 2.3, as illustrated in Figure 13.

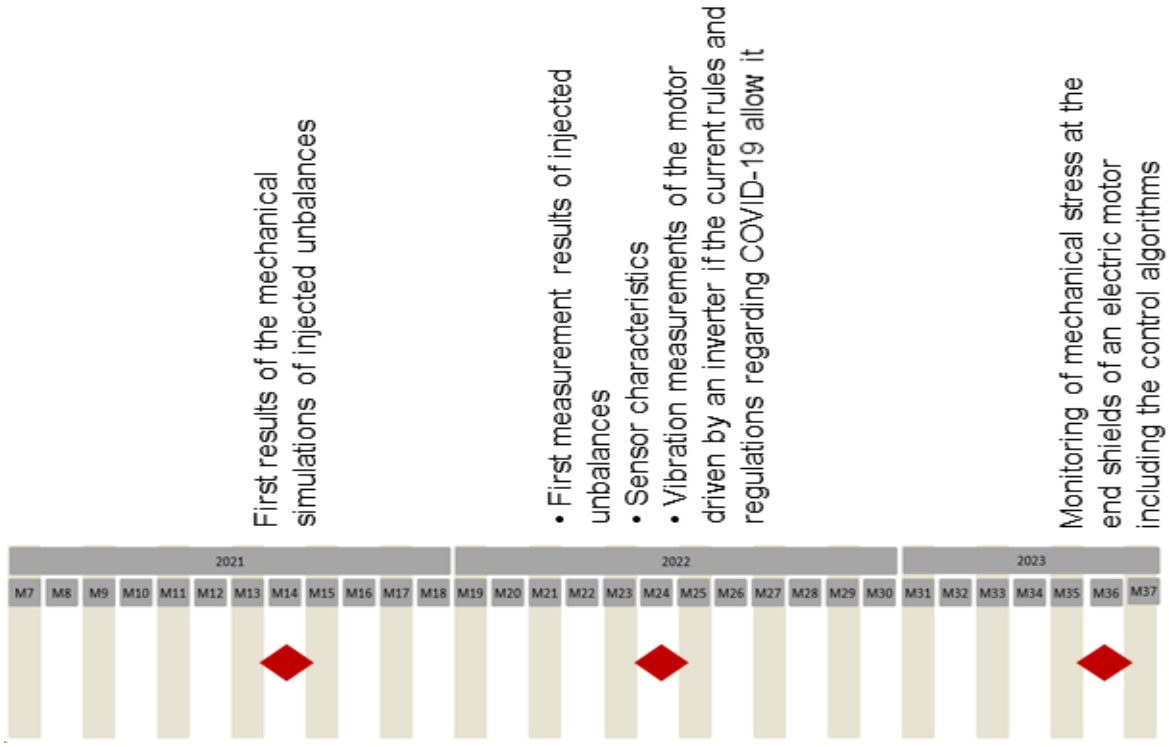

FIGURE 13: DEMONSTRATOR 2.3 MILESTONES TIMELINE

8 Secure MonDev (demonstrator 2.4)

Demonstrator 2.4 is a secure monitoring device based on the OSAM keystone tool suite of DATA.

8.1 Target goals and achievements

The Monitoring device (MonDev) is realized by the OSAM keystone tool suite. It provides monitoring and debugging alongside the OSI model starting from the device driver level until the application covering the ECU level.

The MonDev provides a secure real-time monitoring and test of SW components at runtime, ensuring safety and security by design.

8.2 Demonstrator structure

The keystone tool is a virtual development and test environment enabling the development, test and monitoring of OSAM SW components as shown in Fig.14.

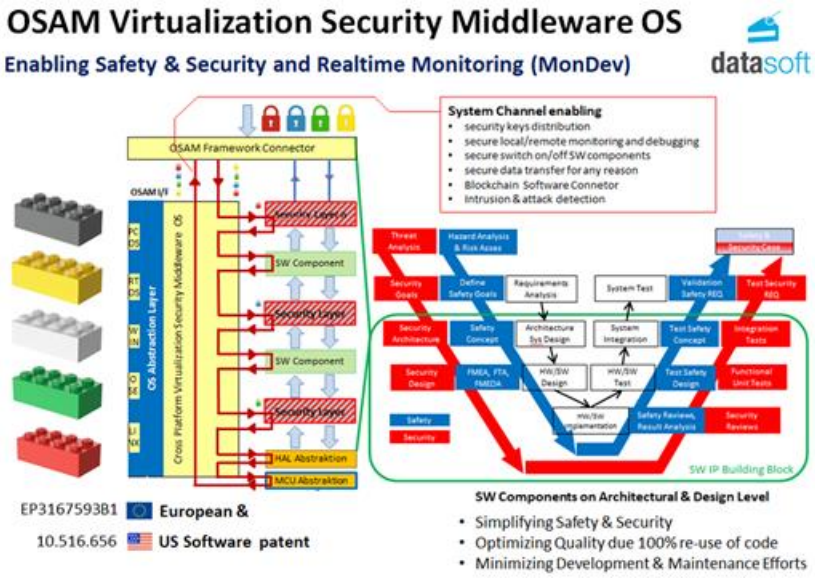

FIGURE 14: DEMONSTRATOR 2.4 STRUCTURE

8.3 Demonstrator description

Fig. 15 shows the planned outline of the Keystone tool as the MonDev. It allows visualization of processes as well as technical monitoring in real time. The concept is modular according to specific demands. Due to this the delivery is limited to REQ only.

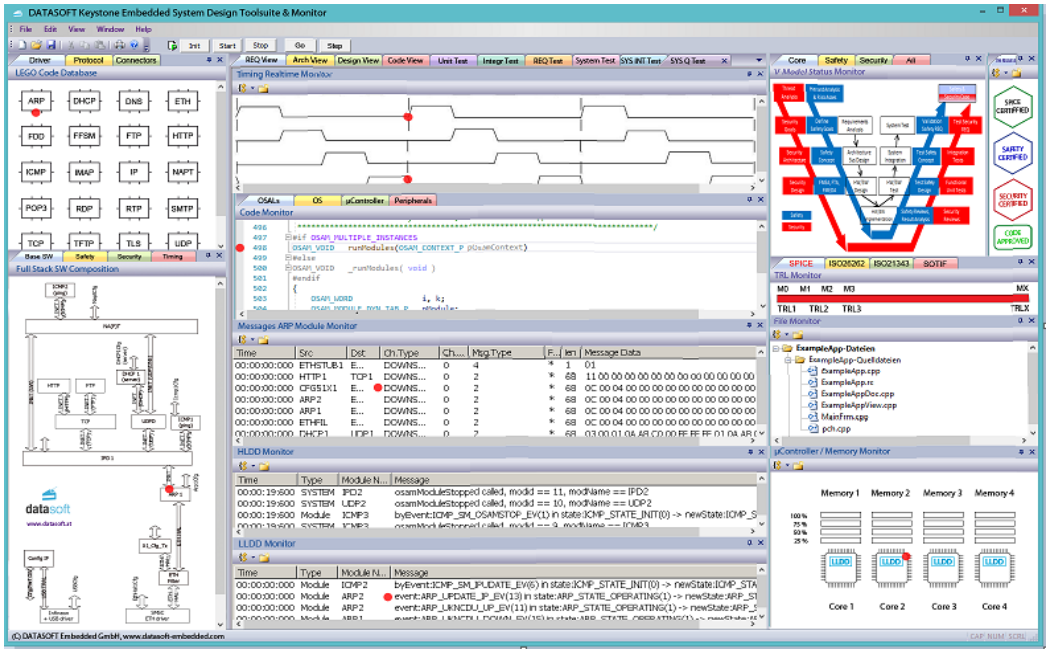

FIGURE 15: DEMONSTRATOR 2.4 OVERVIEW: SECURE MONDEV

8.4 Residual risks

The MonDev demonstrator provides safety and security related features enabling a decrease of residual risks in the development and test of SW components due to the OSAM design methodology (safety & security by design).

8.5 Demonstrator relations to the main objectives and key targets

The MonDev demonstrator fits into the project objectives related to robust design, safety, and quality improvement.

8.5.1 Objectives

O1 - Continuous robust design optimization for each part in the ECS value chain (Technical): Safety and security by design, including a 100% reuse of code.

O2 - Framework for safety validation of ECS value chain (Technical): ISO 26262 approaching ASIL-E (H&R analysis).

O5 - Zero emissions, crashes, and congestions by ECA2030 vehicle (Value): This objective is not directly addressed by demonstrator 2.4, which however contributes to quality improvement due to the OSAM methodology.

8.5.2 Key targets

KT1 - Architectures, components, sub-systems enabling virtual development and validation (monitoring device, failure risk): This demonstrator mainly addresses the SW monitoring in conjunction with safety and security issues.
KT2 - Methods and tools to validate the models used in virtual validation (lifetime monitoring, residual risk, methods, and tools): see KT1.

8.6 Homologation framework mapping

The keystone tool does not affect the homologation framework.

8.7 Non-functional requirements, KPIs, and measures

For the secure monitoring device, we identified three main non-functional requirements, described in Table 28, Table 29, and Table 30.

TABLE 28: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – MONITORING ALONG OSI MODEL

NFR	Monitoring along OSI model
NFR definition	Apply MonDev functionality to monitor & debug alongside the OSI model as a tool
KPI name	Realtime inspection and debugging
Description	The MonDev is supported by the keystone tool in the OSAM Virtualization Security Middleware OS as shown in Fig. 15
Measure	Debugging and monitoring
Type of measure	SW
Method of collection and measurement	
Demonstrator target	MonDev

KPI for Verification and validation	

TABLE 29: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – MONITORING AT DEVICE DRIVER LEVEL

NFR	Monitoring at device driver level
NFR definition	Apply MonDev functionality to monitor & debug on device driver level as a tool
KPI name	Realtime inspection and debugging
Description	The MonDev is supported by the keystone tool in the OSAM Virtualisation Security Middelware OS as shown in Fig. 15
Measure	Debugging and monitoring
Type of measure	SW
Method of collection and measurement	
Demonstrator target	MonDev
KPI for Verification and validation	

TABLE 30: NFRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – MONITORING AT CHIP LEVEL

NFR	Monitoring at chip level
NFR definition	Apply the tunnel effect to enable monitoring on chip level
KPI name	Lowest energy probing
Description	Tunnel effect based elements enabling probing of signals with low disturbance.
Measure	Debugging and monitoring
Type of measure	Signal processing
Method of collection and measurement	
Demonstrator target	ECU
KPI for Verification and validation	

8.8 Functional requirements, KPIs, and measures

For the secure monitoring device, we identified three principal functional requirements, presented in Table 31, Table 32, and Table 33.

TABLE 31: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – FRONT-END AND BACK-END INTERFACES

FR	Front-end and back-end interfaces
FR definition	The Keystone as a tool that provides a front end and a backend interface based on the OSAM architecture.
KPI name	Simplify secure monitoring by design
Description	The keystone tool is split in a front- and a backend enabling a flexible use.
Measure	Debugging and monitoring
Type of measure	SW
Method of collection and measurement	
Demonstrator target	MonDev

KPI for Verification and validation	

TABLE 32: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – MONDEV TOOL FUNCTIONALITY

FR	MonDev tool functionality
FR definition	The functionality of the MonDev as a tool derives from the OSAM architecture.
KPI name	Simplify secure monitoring by design
Description	The Keystone tool is part of the OSAM security middleware.
Measure	Debugging and monitoring
Type of measure	SW
Method of collection and measurement	
Demonstrator target	MonDev
KPI for Verification and validation	

TABLE 33: FRS, KPIS AND MEASURES FOR DEMONSTRATOR 2.4 – MONDEV CHIP LEVEL INSPECTION

FR	MonDev chip level inspection
FR definition	Enable minimum energy consumption by applying the tunnel effect for inspection on chip level (MonDev).
KPI name	Lowest energy real-time monitoring
Description	See Table 30.
Measure	Debugging and monitoring
Type of measure	Signal processing
Method of collection and measurement	
Demonstrator target	ECU
KPI for Verification and validation	

8.9 Mapping to existing standards

The following standards are relevant for the realization of a secure monitoring device.

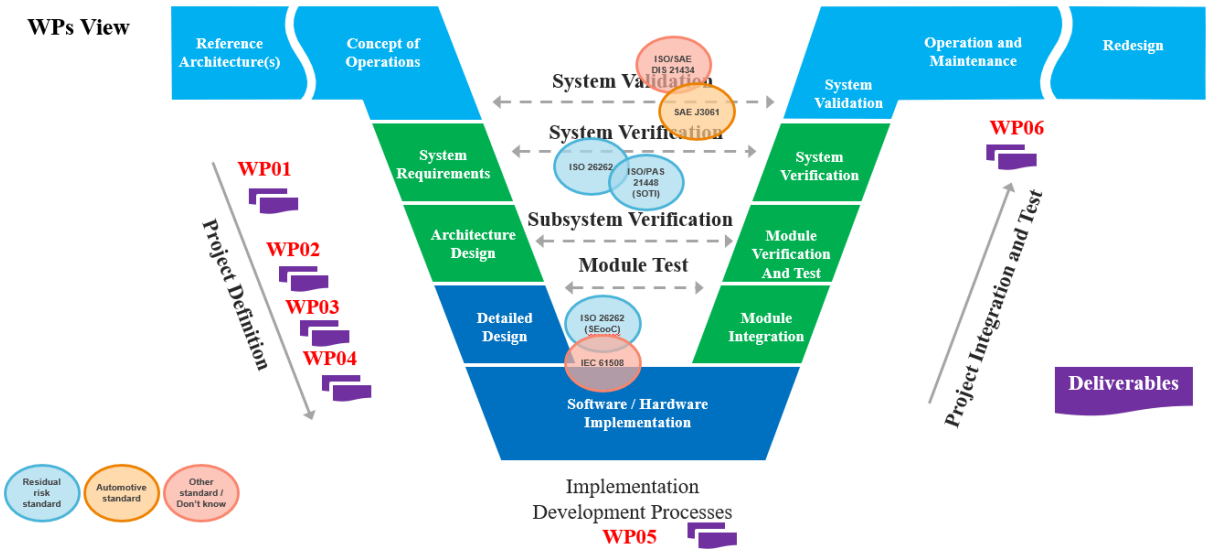

FIGURE 16: DEMONSTRATOR 2.4 - STANDARDS MAPPING V-MODEL ARCHITECTECA2030

TABLE 34: MAPPING OF EXISTING STANDARDS FOR DEMONSTRATOR 2.4

Standard code	Standard title	Why relevant	How to use
ISO 26262	Road vehicles - Functional safety	Address safety-related systems that include one or more E/E systems and that are installed in series production passenger cars (with a maximum gross vehicle mass up to 3 500 kg).	Related to H&R analysis.
ISO/PAS 21448:2019 (SOTIF)	Road vehicles - Safety of the intended functionality	This document provides guidance on the applicable design, verification and validation measures needed to achieve the safety of the intended functionality.	Related to virtual design, verification and validation of safety & security certified SW components.
IEC 61508 (Eight parts 0-7)	Functional safety of electrical/electronic/programmable electronic safety-related systems	Address aspects to be considered when electrical/ electronic/ programmable electronic (E/E/PE) systems are used to carry out safety functions. Requirements for ensuring that systems are designed, implemented, operated, and maintained to provide the required safety integrity level (SIL).	Related to H&R analysis.

ISO/SAE FDIS 21434	Road vehicles - Cybersecurity engineering. (Under development. Stage 50.00, Final text received or FDIS registered for formal approval).	Specifies requirements for cybersecurity risk management regarding engineering for concept, development, production, operation, maintenance, and decommissioning for road vehicle E/E systems, including their components and interfaces. Defines a framework that includes requirements for cybersecurity processes and a common language for communicating and managing cybersecurity risk. Does not prescribe specific technology or solutions related to cybersecurity.	Related to virtual design, verification and validation of safety & security certified SW components.
SAE J3061	Cybersecurity Guidebook for Cyber-Physical Vehicle Systems, (January 2016).		Related to virtual design, verification and validation of safety & security certified SW components.
IATF 16949:2016	Technical specification - Quality management systems for automotive production and relevant service parts organisations, (1st edition, October 2016).	IATF 16949:2016 is aligned with structure and requirements of ISO 9001:2015. IATF 16949:2016 replace ISO/TS 16949:2009 which is withdrawn. IATF 16949:2016 is coupled with the applicable customer-specific requirements, defines the quality management system (QMS) requirements for automotive production, service, and accessory parts. IATF 16949:2016 is an autonomous QMS standard that is fully aligned with the structure and requirements of ISO 9001:2015. However, it is not a stand-alone document, but is implemented as a supplement to, and in conjunction with, ISO 9001:2015. Related document is "Automotive certification scheme for IATF 16949 - Rules for achieving IATF recognition" (5th edition November 2016).	Related to ISO26262

8.10 Verification and validation

See the tables in the sections presenting the requirements, i.e., Table 28, Table 29, Table 30, Table 31, Table 32, and Table 33.

8.11 Demonstrator milestones

The following milestones are planned to be achieved, as illustrated in Figure 9.

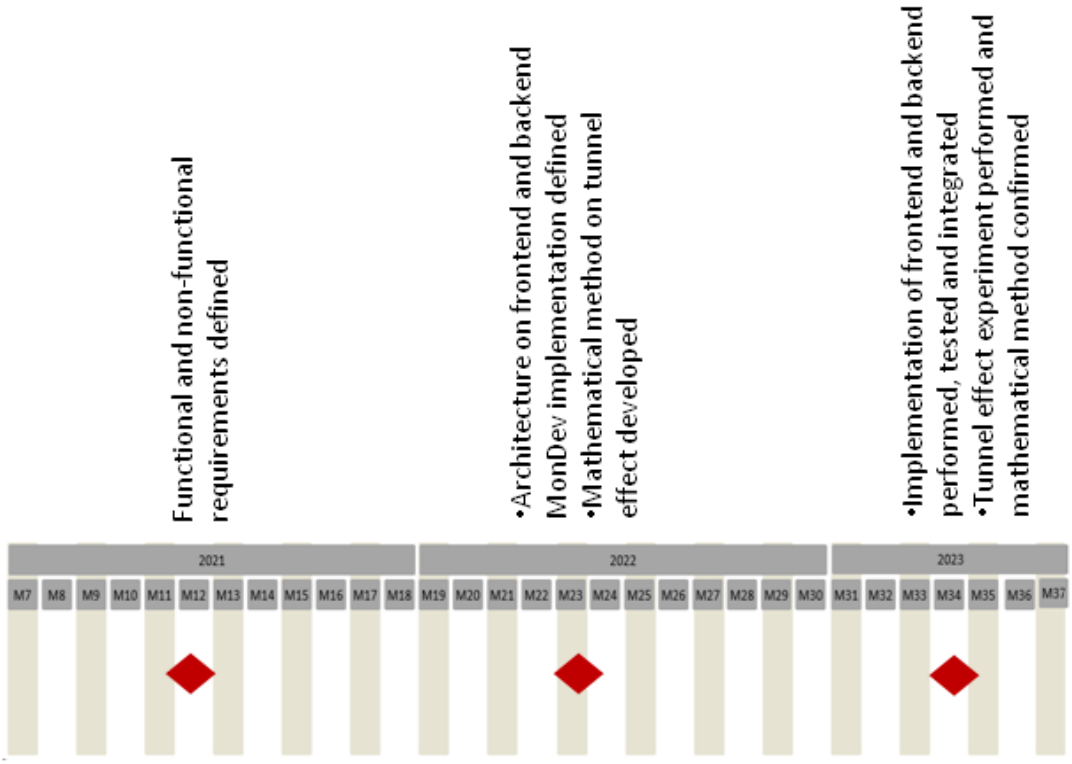

FIGURE 17: DEMONSTRATOR 2.4 MILESTONES TIMELINE

9 SC2 demonstrators summarized

The table below summarizes the standards used in the demonstrators of supply chain SC2.

Standards vs Demonstrators	2.1	2.2	2.3	2.4
AEC Q100	X			
ANSI/UL 4600	X			
IATF 16949				X
IEC 61508		X		X
IEEE P2846	X			
IEEE 1876 TM	X			
ISO 26262:2018 1-12	X	X		X
ISO/IEC/IEEE 25765	X			
ISO PAS 21448 (SOTIF)		X		X
ISO 13373			X	
ISO 20816-1			X	

ISO 10816-3			X	
ISO 21940			X	
ISO/SAE FDIS 21434				X
SAE J3061				X

10 Conclusion

10.1 Contribution to overall picture

The four demonstrators of supply chain SC2 cover various aspects of fault detection for actuators and propulsion systems in electric, connected, and automated cars: monitoring of different components (inverter, thermal controller, motor, monitoring device) for predictive maintenance and estimation of residual risk. The present deliverable contains the specifications of these demonstrators and their requirements; it is thus the basis for the work in the subsequent work packages.

10.2 Relation to the state-of-the-art and progress beyond it

The four demonstrators of supply chain SC2 contribute to the progress of the state of the art, in particular by bringing evolved utilisation of sensors into practical applications. The following table briefly summarizes these aspects for each of the demonstrators.

Partner/Topic	Description
BUT / demonstrator 2.1	**State of the art for condition monitoring and predictive maintenance of inverter power components:** • There exist many scientific papers from last two decades but there is no or rare utilization of these methods in commercial applications. **Progress beyond the state of the art:** • The analysis of possibilities of condition monitoring implementation in the power inverters. • The lifetime and failures prognosis of the IGBTs and DC-link capacitors.
AVL / demonstrator 2.2	**State of the art for safety prediction / residual risk assessment:** • Models for safety prediction, or more specific predictive maintenance / lifetime monitoring, are already available • Those models are usually used in a SiL or HiL setup **Progress beyond the state of the art:** • Usage of these models in a MiL environment • Testing these models against an HV battery, which includes a virtual sensor model • Using these models to perform residual risk assessments
TUDR / demonstrator 2.3	**State of the art for mechanical vibration measurement:** • Usage of external sensors • Typically accelerator and/or microphone are used **Progress beyond the state of the art:** • Sensors integrated in the casing (end shield) of the motor • Usage of 3 strain gauge sensors in addition to a 3-axis accelerator
DATA / demonstrator 2.4	**State of the art for secure monitoring and debugging:** • Proprietary solutions • Limited to ASIL-D • Standardized interfaces **Progress beyond the state of the art:** • Radical reduction on development efforts and costs due Safety & Security by design • 100% re-use of code • Tunnel effect use on chip level for monitoring purposes

10.3 Impacts to other WPs, Tasks and SCs

The present deliverable defines the requirements for the four demonstrators of supply chain SC2, and forms thus the basis, upon which the tasks in the work packages rely. The following table presents these relations in more detail.

Partner/Topic	Description
BUT / demonstrator 2.1	This deliverable defines the functional and non-functional requirements on condition monitoring and predictive maintenance of inverter components and thus prepares the floor for the development of these methods to be used in power trains of the automated cars where the reliability and availability are issues. The work on demonstrator 2.1 is realized in supply chain SC2. The framework fulfilling the requirements from this deliverable will be revealed in WP2 (Task 2.2). The algorithms for fault prediction will be investigated in WP3 (Task 3.2). The algorithms will be integrated, validated and demonstrated on a testbed (demonstrator 2.1). This work will run in WP6 (Task 6.2). It is expected that the condition indicators will be provided to higher layers in the car for storage/long term analysis. This task can be realized in connection with SC4.
AVL / demonstrator 2.2	The foundation of the Co-Simulation, which is developed as part of demonstrator 2.2, will be reused in demonstrator 4.3 “Virtual Verification & Validation Framework” from SC4.
TUDR / demonstrator 2.3	The requirements presented here form the basis for the further processing of the project by TUDR within SC2. They are used in the work packages WP2, WP3, WP5 and WP6 and thus also in the tasks T2.2, T3.2, T5.2 and T6.2.
DATA / demonstrator 2.4	The Keystone tool (MonDev) combined with the OSAM security middleware can be introduced at all software related issues, where safety and security is relevant.

10.4 Contribution to demonstration

The present deliverable is fundamental for the demonstration, as it presents the requirements of the four demonstrators, together with initial ideas for their realization.

Partner/Topic	Description
BUT / demonstrator 2.1	Section 5 describes the requirements on demonstrator 2.1. It also shows the initial ideas about the characteristic features of this demonstrator.
AVL / demonstrator 2.2	AVL contributes directly to demonstrator 2.2. For this demonstrator, AVL will provide a model of a thermal controller in a Co-Simulation. This model will be the system under test for other partners’ contributions. Furthermore, AVL will contribute a predictive maintenance and residual risk assessment method that will also be tested on the former mentioned thermal controller.
TUDR / demonstrator 2.3	The requirements define the main focus to be shown with the planned demonstrators. The TUDR focuses on the detection of faults of an electric drive motor, which become noticeable through mechanical vibrations.
DATA / demonstrator 2.4	The requirements describe the intended use of the Keystone tool and the tunnel effect.

10.5 Other conclusions and lessons learned

The present deliverable presents the four demonstrators of supply chain SC2, which were elaborated during meetings between the involved partners. The following table lists conclusions and lessons learned beyond the better understanding of the objectives and goals of the partners.

Partner/Topic	Description
BUT / demonstrator 2.1	The initial experiments and study will be realized using high power computing platform. If successful, the algorithms will be implemented in the laboratory inverter.

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12 List of figures

13 List of tables

14 Internal Review

	Reviewer 1: Marlies Mischinger	Reviewer 2: Ovidiu Vermesan

1. Is the deliverable in accordance with:

	Answer	*Comments*	*Type**	*Answer*	*Comments*	*Type**
(i) the description of work?	No	I added my comments directly in this report as well as in a separate document. In general, this document does not reflect the complete work in task 1.2, and it suffers from contribution by the task itself.	M	yes/no		M/m/a
(ii) the international state of the Art?	No	The „state of the art" should be removed from the conclusion section. It should be added to the demonstrators and should be extended in any case. In general, an international comparison/ state of the art is not available in this document.	M	yes/no		M/m/a

2. Is the quality of the deliverable in a status that:

		Answer	*Comments*	*Type**	*Answer*	*Comments*	*Type**
	allows to send it to ECSEL JU?	No	All comments have to be revised and missing inputs from partners (DATA, UNEV) must be added, accordingly to the task description.	M	yes/no		M/m/a
(ii)	needs improvement of the writing by the authors of the deliverable?	Yes	See my comments.	M	yes/no		M/m/a
(iii)	needs further work by the partners responsible for the deliverable?	Yes	See my comments.	M	yes/no		M/m/a
(iv)	Needs to fulfill the following suggestions?	Yes	There are task participants that should contribute to the deliverables too. Not only the task leader is in charge for filling the deliverables with text.	a	yes/no		M/m/a

* Type of comments: M = major comment; m = minor comment; a = advise

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