The project has been accepted for funding within the Key Digital Technologies Joint Undertaking (KDT JU), a public private partnership in collaboration with the Horizon Europe (HORIZONI Framework Programme and National Authorities under grant agreement number 101096387.

PowerizeD

Digitalization of Power Electronic Applications within Key Technology Value Chains

Deliverable	**D2.1.5. Summary report on results on Cross Application & Domain Topics of methods for reliability, modelling & digital twins**		
Involved WPs	WP 2	**Deliverable type**	Public
Project	PowerizeD	**Grant Agreement Number**	101096387
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TABLE 1.

Document history

V	Date	Author	Description
0.1	19/11/2025	Dag Andersson, all partners	Initial Version
0.1	19/11/2025	-"-	Draft for Review to guarantee public release
0.1	25/11/2025	Vesa Vuorinen, all partners	First internal review by Vesa Vuorinen
0.2	04/12/2025	Dag Andersson, all partners	Next to final Version
0.3	06/12/2025	Dag Andersson	Final version for review
0.3	07/12(2025	Vesa Vuorinen	Final internal review
1.0	08/12/2025	Dag Andersson	Final version for submission

TABLE 2.

1 Contents

2 Summary

Project acronym	**PowerizeD**
Project Logo	PowerizeD Digitalization of Power Electronic Applications within Key Technology Value Chains
Project full title	Digitalisation of Power Electronic Applications within Key Technology Value Chains
Project Coordinator	Mr. Jochen Koszescha, Jochen.koszescha@infineon.com Infineon Technologies AG
Coordinating Entity	Infineon Technologies AG

TABLE 3.

The D2.1.3 deliverable of the PowerizeD project includes the main progress and final results on Cross Application & Domain Topics (CDT) methods for Reliability (CDT1.1), Modelling (CDT1.2) & Digital Twins (CDT1.3). Cross cutting aspects in relation to methods, strategies and complementarities among Tasks 2.1.1 (Reliability), Task 2.1.2 (Modelling) and Task 2.1.3, (Digital Twin) as part of WP2.1 are fully demonstrated.

Smart power electronics must function reliably for 10 to 40 years under the harsh conditions encountered in mobility (e.g., automotive), industry, and energy applications, where they perform safety-relevant tasks. Consequently, new approaches are needed to increase the efficiency of reliability assessments by at least an order of magnitude—for example, reducing the assessment period from a full quarter to just one week—while maintaining thoroughness and comprehensiveness. Alongside the next generation of physical tests and analysis methods (T2.1.1), digitalization is the key enabling factor for achieving this improvement. In WP2.1, highly efficient modelling approaches (T2.1.2), a new type of digital twin (T2.1.3), and the necessary AI-based controls (T2.1.4) will be developed to meet this challenge.

3 Introduction & Scope

3.1 Purpose and target group

Each of the aforementioned CDTs have held regular meetings, where interested partners have shared ideas and insights based on their respective use cases. Each section of this report corresponds to a specific CDT, and subsections are defined according to the relevant use cases (UCs) to present concepts pertinent to that CDT.

3.2 Relation to other activities in the project

	Reliability, Modelling & Digital Twins							
Domain	**Leader**	**UC (new)**	**UC Title**	**Leader**	**CDT1.1**	**CDT1.2**	**CDT1.3**	**CDT1.4**
					Reliability	**Modelling**	**Digital Twins**	**Federated Learning**
Intelligent Energy for Mobility	**MBAG**	1.1	Railway Propulsion Systems	ALSTOM	x	x	x	x
		1.2	PEBB for Traction Converters	IPT		x	x	X*
		1.3	PEBB for DCDC Converters	IPT		x	x	X
		1.4	BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage	SCANIA	x	x	x	
		1.5	FCEV- Fuel Cell and Powertrain Inverter	RB	x	x	x	x
		1.6a	Mobile In-Line Charger (MILCA) & Large Power Stationary Charger	XC				
		1.6b	Medium Power Modular Stationary Charger	ELC	x	x	x	x
		1.6c	Large Power Stationary Charger	PRE	x	x		

		1.7	Charging infrastructure	OTH/EDI			x	x
Renewables, Grids & Lighting	**SIGN**	2.1	Flow battery power electronics	AQUA	x		x	
		2.2	Power Electronics for Green Hydrogen	PRO	x	x	x	
		2.3	LED-Driver and LV DC Distribution Grid	SIGN		x	x	
		2.4	Personal Mini PV with Storage	FPG				
Industrial Drives	**ABB**	3.1a	Prognostics for industrial Drives	ABB	x	x		x
		3.1b	Intelligent Gate Driver for Industrial Inverter	ABB/TUDD				
		3.1c	Improved drivetrain efficiency	ABB	x			
		3.2	New hyper-sensorised digital drive	FAGOR	x	x	x	

TABLE 4.

4 CDT 1.1 Reliability (Task Lead – TUDE)

The new approach to reliability assessment is defined by a close integration of experimental and virtual methods, with experimental tests and analyses forming the foundation. These tests provide essential information about critical failure modes and the expected lifetime under field conditions. They also enable the calibration, training, and validation of all models, digital twins, and AI methods, which perform the bulk of the reliability assessments. While most Design of Experiment (DoE) variants have been analysed virtually, the methods and tools used have first been rigorously validated through experiments.

To establish reliable anchor points across the entire relevant design space and use case scenarios—whose scope is expanding due to the increasing complexity of smart power electronic systems and the growing diversity in applications—a next generation of experimental test and analysis methods is required. These methods must achieve two key objectives:

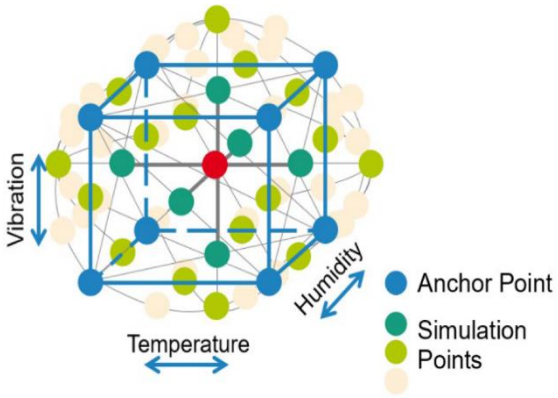


FIGURE 1.

1. **End-of-Life (EoL) Assessment (ST2.1.1.1):** Effectively and comprehensively assess the total lifetime of products under development in their future field use by determining the typical duration until EoL and identifying the responsible failure mechanisms.
2. **Remaining Useful Life (RUL) Estimation (ST2.1.1.2):** Estimate the RUL of individual electronic systems deployed in applications (e.g., in cars) while in use by end customers.

Subtask 2.1.1.1: End-of-Life (EoL) Assessment

- Development of accelerated stress tests that combine multiple loading conditions simultaneously, reflecting field use, and creation of lifetime estimation models for these tests.
- Development of new analysis methods to capture transient behaviours and aging effects, rather than relying solely on static considerations with fresh samples.

Subtask 2.1.1.2: Remaining Useful Life (RUL) Estimation

- Identification of early warning indicators for detecting physical degradations (Physics of Degradation (PoD) approach) in device and package structures during field use, and derivation of RUL estimation models.

- Discovery of new correlations between parameter drifts and RUL (Data Driven (DD) approach) and development of higher-level indicators (e.g., "pain factors") for monitoring entire modules and systems during field use.
- Integration of PoD and DD approaches into a comprehensive Prognostics and Health Management (PHM) concept.
- Development of methods for real-time dynamic adaptation of operation modes to extend RUL when degradation effects are detected that could lead to system failure.
- Enhanced failure prevention and mitigation through improved understanding of degradation and failure mechanisms at device and system levels.
- Creation of strategies for system reconfiguration in the event of failure, ensuring extended RUL and continuous operation despite degradation or faults.

4.1.1 UC 1.1 Railway Propulsion Systems

Use Case	Railway Propulsion Systems
Partners	ALSTOM, KTH, RISE, IFAG
Reliability Assessment	
Development of a test system and AI augmented method for non-destructive accelerated lifetime and robustness testing of power semiconductor modules in rail and non-rail e-mobility applications. This should include varying temperature and output power. The solution should also enable more accurate relevant mission profile testing for reliability and design robustness during normal and more extreme operating points in addition to lifetime testing. Once designed, the solution shall be implemented in a multi-purpose converter load test system. Furthermore, reliability assessment and detection methods for gate oxide degradation will be developed for implementation in inverter control electronics.	
Limit of today's reliability assessment:	With the advent of new power semiconductors such as SiC, reliability, design robustness and lifetime are key to a successful market introduction. However, existing test methods and systems in this domain rely primarily on reaching destructive failures. Nor do robustness and reliability test methods lend themselves to easily account for actual mission profiles and application conditions.
Target of improving reliability assessment:	▪ Accurate Remaining Useful Life / End of Life predictions for power semiconductor modules from non-destructive testing methods ▪ Accurate reliability and robustness assessments ▪ Shortened test duration ▪ Test system for reliability, lifetime and robustness testing with ability to mimic mission profile conditions ▪ Enable Alstom Open Powerlab to provide reliability and robustness test services to external partners and clients
Summary of results	
Developed temperature and drift compensation techniques to enable reliable health diagnostics of SiC MOSFET packages. Established a fully integrated, FPGA-controlled power cycling system for precise and automated thermal and electrical stress testing. Demonstrated the feasibility of non-destructive, parameter-based degradation monitoring to predict device lifetime and failure onset.	

TABLE 5.

4.1.2 UC 1.4 BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage

Use Case	BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage
Partners	SCANIA, KTH, ALSTOM, RISE, IFAG, SAL

Reliability Assessment

Development of accelerated stress tests based on real vehicle operational data from a battery electric heavy-duty vehicle (BEHVD). Thermal cycle tests with active (power cycling) and passive (temperature cycles) loads combined, in order to find the correlation between the number of cycles and the lifetime of the component. The lifetime test methods will include multiple loading conditions like junction temperature, ambient temperature, and humidity included.

Development of a RUL estimation method for power components and devices by devising and implementing a number of fault injection techniques prior to testing. Also, development and implementation of a RUL estimation on a system level, i.e. inverter.

Limit of today's reliability assessment:	With the advancement of electrification in the automotive sector, new state-of-the-art automotive-grade power modules with advanced materials and topologies are being introduced into the market. For BEHDV, these power modules are expected to endure more than 50,000 operating hours under various operating conditions. With the introduction of advanced packaging, there is a need to reevaluate the lifetime assessment studies and tests and develop next-generation test methods to aid in end-of-life assessment. Shorter testing period with testing conditions close to the reality is desired. Moreover, new failure indicators in these advanced packages need to be identified, which can later be used to estimate the remaining useful lifetime.
Target of improving reliability assessment:	New knowledge in the field of Prognostics and Health Management (PHM), will be used to design optimal functionalities for the drive inverter, e.g.; ▪ Diagnostic capability that can predict failures and remaining useful life length of components and systems. ▪ Service and maintenance of the vehicle will be optimized. ▪ The need for over sizing components and systems will be reduced significantly. ▪ This will enable a possibility for future PHM business. Develop lifetime models based on physics of failure and machine learning methods, using data from a multitude of vehicles operating daily and being connected to a cloud-based data collection centre. For example, monitoring the behaviour of the on-state resistance of the MOSFETs.

Summary of results

Developed compensation methods to compensate **temperature** and **threshold voltage drift** related changes in **ON-state resistance** of SiC MOSFET Devices. Below are the compensation methods:

Temperature compensation:

i. The relation in between junction temperatures and ON-state resistance is calculated using the measurement points.

ii. This relation, measured ON-state resistance, and measured junction temperature are then used to compensate the temperature dependence of ON-state resistance. iii. The temperature compensated ON-state resistance represents changes related to Vth-drift or package degradation. iv. Finally, differentiator with a moving average filter and recursive least square estimators are used to compensate Vth related drift. v. The compensated ON-state resistance successfully identifies bondwire related failures in SCT30N120. vi. It also helps in early detection of the bond wire related failures in packages with multiple bond wires, like C2M0160120D Drift compensation: i. The temperature-compensated ON-state resistance (ΔR̂dsON,max) still includes effects from Vth drift and package degradation. ii. The linear portion of ΔR̂dsON,max, showing a gradual increase, is attributed to Vth drift-related die degradation, while the non-linear rise indicates package-level degradation such as bond wire lift-off. iii. Two methods are applied to separate these effects based on slope estimation: a moving-window first-order polynomial fit and a derivative-based technique with post-filtering. iv. Both methods effectively distinguish between the linear (die-level) and non-linear (package-level) regions of degradation. v. The polynomial fitting method provides smoother and more stable slope estimation, particularly for smaller window sizes, and is less sensitive to noise compared to the derivative-based method. vi. The drift-compensated ON-state resistance thus enables reliable differentiation between Vth drift and package-related failures in SiC MOSFET devices. Publications: ECCE Europe: B. P. Singh, S. S. Ghahfarokhi, E. Ayaz, H. -P. Nee and S. Norrga, " SiC MOSFET Condition Monitoring using Compensated ON-State Resistance for Identifying Package Failures," 2025 Energy Conversion Congress & Expo Europe (ECCE Europe), Birmingham, U.K., 2025 ECCE America: B. P. Singh, H. -P. Nee and S. Norrga, " Online Condition Monitoring of Bond Wire Degradation using Temperature Compensated ON-state Resistance," 2025 Energy Conversion Congress & Expo America (ECCE America), Philadelphia, USA, 2025

TABLE 6.

4.1.3 UC 1.5 FCEV- Fuel Cell and Powertrain Inverter

Use Case	FCEV- Fuel Cell and Powertrain Inverter
Partners	FHG, MBAG, Bosch
Reliability Assessment	
FhG ENAS plans to develop new experimental reliability tests that combine active and passive thermal cycling. MBAG is investigating methods for determining the health status and remaining lifetime of power electronic and e-drive components through on-board monitoring. RB is exploring a new Design for Reliability (DfR) approach to accurately evaluate the effect of extended use-case conditions on the reliability of design elements. In addition, RB is developing a	

hybrid Prognostics and Health Management (PHM) approach for these design elements, considering both active and passive cycling.	
Limit of today's reliability assessment:	The single-load reliability tests currently in widespread use can only partially reflect real load conditions and, for example, cannot account for interactions between individual failure modes. Initial approaches to combining different load factors (e.g., active and passive temperature changes) have already been investigated, but further work is needed to gain a better understanding. Power electronic devices in electric vehicles feature basic self-diagnostic functions that allow for fault detection at the moment of occurrence. However, there is no indication of accumulated damage over the component's lifetime, nor any indication of degradation or imminent failure.
Target of improving reliability assessment:	A better understanding of the quantitative and qualitative failure behaviour of SiC-based power modules under combined loading conditions is required. For this purpose, the test results will also be compared to the results of state-of-the-art (single load) tests. By measuring certain physical parameters within the e-drive component, we hope to identify patterns or relevant indicators that provide information about the component's current state of health and enable the prediction of its remaining useful life or safe operating area
Summary of results	
FhG: Reliability testing of TO247 modules, development of lifetime model, studying the bonding wire failure mechanisms, using the power cycling test data for training of Federated Learning model within CDT1.4 Federated Learning. **Bosch:** End of life data from the Board Level Reliability test has been gathered with statistical significance of more than 90% of failed components. Using the end-of-life data lifetime modelling is enabled on the basis of both passive and active cycling. 2. Conduct a functional test of the SiC-based power module with the integration of digital twins. This will allow us to investigate how the algorithm developed in PowerizeD by consortium partners can be used for prognostics and health management.	

TABLE 7.

4.1.4 UC 1.6b Medium Power Modular Stationary Charger

Use Case	Medium Power Modular Stationary Charger
Partners	ELC, UNIBO, SERI, IFI, IFAG, IFAT, FPG, HEPO, ETHZ, KEMP
Reliability Assessment	
Limit of today's reliability assessment:	
Target of improving reliability assessment:	Objective of the project is the realization of a new generation charging stations with higher power density, but still reliable. To achieve these targets, a novel concept for an intelligent SiC power module will be developed, able to integrate the power switches of the DC-DC converter, the gate driver board and the current, voltage and devices' temperature measurements.

Summary of results
A novel DAB-based architecture for a 1200 V Intelligent power module, which integrates all the power devices of the primary and secondary side of DAB architecture, has been manufactured based on Alumina DCB and IMS. IMS-based power module has been manufactured with materials selection based on an extensive aging test campaign performed in CDT 2.1 Substrates.

4.1.5 UC 1.6c Large Power Stationary Charger

Use Case	UC 1.6c Large Power Stationary Charger
Partners	PRE, VSL, TUDE
Reliability Assessment	
To test the reliability of the new developed power electronics we will use a high current power cycler (600 A) for stress testing. Furthermore, VSL will design a test method to measure the efficiency (power losses) of the power conversion.	
Limit of today's reliability assessment:	Device specific failure mode and failure rate data is not available easily. System level reliability based on number of components and topology dependent stresses on these components (mission profile) needs further investigation.
Target of improving reliability assessment:	At the end of the project we will demonstrate a reliable and very efficient high power charging infrastructure. To demonstrate this, we use VSL's test set-up. The test set-up will measure the losses due to power conversion and heat. TUDE's 600 A active power cycler will be used to generate experimental data with accelerated lifetime tests for Si and SiC devices. We want to set junction temperature swing (dT), on-time (Ton) and cycle time (Tcycle) and measure the degradation based on thermal parameters (Rth-Cth), and on-state voltage (Von).
Summary of results	

Research - Discovered an early sign of degradation in silicon carbide MOSFETs. Developed algorithm is experimentally validated with multiple samples for different temperature swings. **Technical -** Developed a power cycling testbed capable of imposing consistent temperature swings on multiple samples while monitoring degradation parameters under accelerated conditions. Test conditions like cycle time and temperature swing were optimized to obtain fast degradation under controlled conditions. **Education:** 1 Phd student is on good track, and 1 MSc student has graduated. Course lectures and tutorial sessions are designed and implemented. **Conference Papers:** • M. Molenaar, F. Kardan, A. Shekhar and P. Bauer, "Power and Thermal Cycling Testbed for End of Life Assessment of Semiconductor Devices," *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, Singapore, 2023 • M. Molenaar, A. Shekhar and P. Bauer, " Monitoring the degradation of SiC MOSFETs undergoing thermo-mechanical stresses," *IECON 2025- 51st Annual Conference of the IEEE Industrial Electronics Society*, Madrid, Spain, 2025, pp. 1-6. **Journal Draft in Peer Review Process:** • M. Molenaar, A. Shekhar and P. Bauer, " Early End-of-Life Indicator for Condition Monitoring of Silicon Carbide Power MOSFETS," Draft under journal peer review.

TABLE 8.

4.1.6 UC 2.1 Flow battery power electronics

Use Case	Flow battery power electronics
Partners	AQUA, TUDE
Reliability Assessment	
The X50 Version 2 (X50v2) membrane stack encountered several issues during assembly and testing. This iteration was specifically designed to address many of the shortcomings of the first version, namely structural failures of the dividers and compression. Instead of undertaking a complete redesign, only select features will be reworked to resolve these problems. Meanwhile, for the power electronic interface, we seek to assess the influence of component count and operating stresses on the converter's predicted lifetime. Modelling of the Dual Active Bridge (DAB) converter analytically in Python to evaluate power losses, thermal stresses and reliability of the converter. The model uses Rainflow counting, Monte Carlo analysis, Miner's rule, and the CIPS switch reliability model to evaluate the reliability of various devices, which are then used to evaluate the converter. An alternate model was developed in PLECS to simulate the DAB converter and then calculate power losses and device temperatures. Both the models are compared together for accuracy. The PLECS model is also used to tune the PI controller for a specific converter design and operational parameters.	
Limit of today's reliability assessment:	The losses are based on the datasheet figures of the MOSFET used. The Switch loss model thus created gets more inaccurate as the operational parameters change. To verify reliability, new analysis methods must be developed. Since Ansys is part of the PowerizeD project, we acquired the software to build a finite element analysis (FEA) model incorporating data from Instron machine tests. For power electronic systems, reliability is still

	often evaluated using an outdated Military Handbook that does not accurately reflect the failure rates of modern components.
Target of improving reliability assessment:	Consequently, robust testing, characterization, and failure analysis methods are needed to validate the interfaces among spacers, membranes, and stack dividers. This approach will help improve overall reliability while reducing both internal and external leakage in the membrane stack. At the system level, we plan to determine the reliability of the power electronic interface using failure data obtained from consortium partners. These findings will enable us to select the most reliable grid interface for the flow battery. The converter model requires more fine tuning for loss and device temperature calculation. The transformer losses will have to be added.
Summary of results	
– Identified quantitatively that reliability to DAB bridges is different due to asymmetric charge-discharge characteristics of the flow battery. – Suggest a strategy for converter reliability enhancement by reconfiguring bridges during normal operation.	

TABLE 9.

4.1.7 UC 3.1a Prognostics for industrial Drives

Use Case	**Prognostics for industrial Drives**
Partners	**ABB, AALTO, BME, BNT, BUTE, IFX, NANOJ & SAL**
Reliability Assessment	
ABB is executing end-of-life (EoL) assessment by exposing the power semiconductor modules to combined thermal-power cycling stresses (i.e. Bicycle test [1] or superimposed test [2]) for Econo3 modules to compare the reliability performance of novel interconnection solutions (see CDT2.2) to standard modules with SAC die-attach with the integrated on-chip temperature sensor [3-6]. Ref [1] G.J. Riedel, M. Valov, (2014), Simultaneous Testing of Wire bond and Solder Fatigue in IGBT Modules, *International Conference on Integrated Power Systems (CIPS)*. [2] A. Otto, X. Liu, *et.al.*, (2023), Study of Power Cycling Tests Superimposed with Passive Thermal Cycles on IGBT Modules, *PCIM Europe Conference Proceedings.* https://doi.org/10.30420/566091024 [3] E.R. Motto, J.F. Donlon, (2012), IGBT module with user accessible on-chip current and temperature sensors, *Conference Proceedings - IEEE APEC*. https://doi.org/10.1109/APEC.2012.6165816 [4] K. Wang, Y. Liao, *et. al.,* (2014), Over-Temperature protection for IGBT modules, *PCIM Europe Conference Proceedings*. [5] B. Wang, H. He, Z. Song, (2019), Highly Reliable Protection of Power Module for Automotive Inverter Application, *PCIM Asia 2019*. [6] M. Otsuki, M. Watanabe, A. Nishiura, (2015), Trends and opportunities in intelligent power modules (IPM), *Proceedings of the ISPSDs*. https://doi.org/10.1109/ISPSD.2015.7123453	
Limit of today's reliability assessment:	No evaluation data for integrated on-chip Tj sensor for predictive health monitoring was available prior to this project. Testing methods and analysis tools utilizing in-situ temperature measurements for reliability assessment in combined loading conditions are lacking.
Target of improving reliability assessment:	Tests, characterization and failure analysis methods need to be developed to verify the reliability of novel interconnection solutions needed for new modules utilizing WBG components. Moreover, the target is to verify if

	there is a correlation between 5% increase in V_{CE} and 20% increase in R_{th}(j-c) with the failure physics (i.e. area of delamination). "Bicycle testing" is executed to IGBT modules using different interconnection methods. Transient thermal characterization is utilized to separate failure mechanisms. The objective is to demonstrate improved lifetime of Econo3 modules using novel interconnection methods over the standard module utilizing SAC die-attach.
Summary of results	
Aalto co-operated with ABB on physics of failure analysis on "Bicycle" tested Econo 3 modules. The failure mechanisms (wire bond lift-off, die attach degradation and system solder fatigue), identified with transient thermal analysis, were verified by utilizing both non-destructive (SAM) and destructive (SEM+EDS) methods.	

TABLE 10.

4.1.8 UC 3.2 New hyper-sensorised digital drive

Use Case	New hyper-sensorised digital drive
Reliability Assessment	
Reliability assessment of the power drive system in machine tools is critical to ensuring consistent performance under demanding operating conditions. Within these systems, capacitors and IGBTs (Insulated Gate Bipolar Transistors) are key components that are subject to a range of stress factors, including high temperatures, voltage fluctuations, and repeated loading cycles. Capacitors—particularly electrolytic and film types—can degrade due to temperature extremes, excessive ripple currents, and aging effects that diminish their capacitance and increase losses. IGBTs, on the other hand, can experience bond wire fatigue, semiconductor chip degradation, and thermal cycling issues that lead to an increased on-state resistance or eventual device failure. A thorough reliability assessment involves accelerated life testing, thermal modelling, and detailed failure analysis of each component, allowing engineers to predict end-of-life behaviours more accurately and implement appropriate design margins or protective circuitry. This ensures that machine tool drives maintain operational stability and extend component life even in harsh industrial environments.	
Limit of today's reliability assessment:	FAGOR currently ensures the reliability of its products through a HALT-HASS methodology, which involves using real products that are destroyed during testing. While this approach is effective at uncovering potential weaknesses, it has several limitations. For instance, the stress levels employed may not accurately reflect real-world conditions, and the limited sample size can reduce statistical confidence. Furthermore, these tests do not account for failures caused by long-term material degradation or the wear and tear that occurs under normal operating conditions. Finally, the cost and effort required to plan and execute HALT-HASS tests can be significant. In response to these challenges, data-driven modelling strategies that combine statistical methods and AI are proposed. Based on the current state of the art, real-time constraints, and the desired system behaviour, the following techniques are initially considered: • **Few-Shot Learning:** Gaussian Process Regression (GPR), Long Short-Term Memory (LSTM), XGBoost (decision trees) • **Transfer Learning:** LSTM + Mixture Density Networks (MDN)

	• **Metamodeling:** Incorporating any or all of the four topologies mentioned above
Target of improving reliability assessment:	FAGOR's goal is to establish more flexible and cost-effective reliability assessment methods. By leveraging datasets gathered under real-world operating conditions, state-of-the-art machine learning techniques can provide a more realistic and representative evaluation of reliability. Drawing on extensive operational data, these methods can enhance statistical confidence in test outcomes and detect long-term degradation patterns that might be overlooked by HALT-HASS tests. In addition, machine learning models can be updated continuously as new data becomes available, enabling a dynamic approach to reliability assessment that avoids starting from scratch after each iterative hardware improvement. Finally, machine learning techniques can be used to develop real-time or near real-time monitoring and predictive maintenance systems.
Summary of results	
1 A dataset of IGBT accelerated aging. A framework for modelling and predicting RUL of power electronic components including confidence intervals. 2 papers published. Cruz et al., Long Short-Term Memory Mixture Density Network for Remaining Useful Life Prediction of IGBTs, ***Technologies*** 2025, 13(8), 321. Cruz et al., A Data-Driven Approach for Predicting Remaining Useful Life of Semiconductor Devices Based on Machine Learning and Synthetic Data Generation: A Review and Case Study on SiC MOSFETs, ***IEEE ACCESS*** 13, 2025, pp. 138834–138850, **Q1**. 1 software registered	

TABLE 11.

5 CDT 1.2 Modelling (Task Lead – CSIC)

Digitalization is crucial for the effective development and operation of smart power electronic systems, demanding comprehensive modelling of functionality, performance, reliability, and safety. While numerous tools and methods currently exist for developing power and sensor electronics using well-established technologies in today's applications, they do not fully address the needs of systems that integrate power and sensor electronics into one platform and target a range of emerging use cases requiring cost-sensitive, high-volume manufacturing.

In particular, the following aspects have studied and researched during project execution.

- **Smart electro-physical models**
  Capture and prevent harmful operating modes. For instance, using a negative gate voltage to reduce on-state resistance in SiC devices can significantly narrow the safe operating area.
- **Real-time assessments**
  Identify threshold voltage shifts and instabilities, parasitic turn-ons, short circuits, or γ-ray impacts well before failure, and enable active protection to enhance power electronics safety.
- **Multi-domain modelling**
  Cover electrical, magnetic, thermal, and mechanical behaviour to address complex loading scenarios in emerging applications that combine multiple types of stresses.
- **Process- and aging-dependent material behaviour**
  Develop precise lifetime estimation methods for field use by incorporating the effects of material processes and degradation.
- **Data-driven modelling with small datasets**
  Implement few-shot, AI-based learning to accelerate model deployment and reduce dependency on large volumes of training data.
- **Accurate degradation models**
  Decrease power device derating while meeting all application requirements.
- **Advanced modelling and simulation tools**
  Facilitate the optimization of design and operation in complex systems, even those comprising multiple power converters, loads, and energy sources.

The main highlights related with modelling are summarized as follows:

1. **AI-Based Modelling Framework (Python/PyQt5)**
   - A computational framework developed in Python and PyQt5 for AI-based modeling
   - Supports training of individual models (e.g., MLP, LSTM, RNN, GRU, Bi-LSTM) or ensembles of models
   - Optional hyperparameter optimization for single models and built-in hyperparameter tuning for ensembles (to address meta-modelling requirements)
2. **Electrothermal-Mechanical Modelling of Power Modules**
   - Physics-based reliability modelling of bond wires using 3D ETM modelling in COMSOL Multiphysics
   - 3D wire geometry defined with Rhino 7 and the MFis Wire plug-in, integrated into COMSOL Multiphysics
3. **BiCycle Simulation Model**
   - Simulation of the BiCycle test setup (combined power and thermal cycling)
   - Includes the R8i LC drive and three DUTs (devices under test) with integrated temperature sensors in the IGBT chip

4. **DC/DC Converter Parameter Identification**
    - Parameter identification using PSO and IPM in a discrete/digital system model
5. **Thermal Analysis of DBC and IMS**
    - Direct Bond Copper (DBC) and Insulated Metal Substrate (IMS) thermal performance evaluation
    - Thermal transient simulations to assess heat flow and thermal response
6. **Insulated Metal Substrate (IMS) Analysis Conditions**
    - Numerical analyses via FloTHERM and SUNRED for thermal transient analysis
7. **Electromagnetic and CFD Modelling**
    - Electromagnetic finite element (FE) modelling of power modules
    - CFD-based temperature calculations for comprehensive thermal assessment
8. **PEM Electrolyser Modelling**
    - Modelling a PEM electrolyser using the PLECS software tool
9. **Power Converter Implementation**
    - Development of the power converter that interconnects the PEM stack with renewable energy source (RES) production

The following tables summarize the specific progress of the research and innovation activities conducted to date in relation to each use case.

5.1.1 UC 1.1 Railway Propulsion Systems

Use Case	Railway Propulsion Systems
Partners	ALSTOM, EDRM
Modelling	
Develop models for improved thermal management in railway propulsion converter design to efficiently utilize new generations of Si IGBTs and SiC MOSFETs	
Limit of today's modelling:	New power semiconductor device generations including both SiC and Si devices can enable more compact designs through their lower losses. However, an optimum utilization requires improved thermal management strategies.
Target of improving modelling:	By developing models to analyse various thermal management strategies it is foreseen that optimum compact and lightweight inverter designs can be achieved.
Summary of results	
Key results include high-fidelity and reduced order models (ROM) of converter including power modules, heatsink and cooling system, with different levels of accuracy, speed, and complexity	

TABLE 12

5.1.2 UC 1.3 PEBB For DC-DC Converters

Use Case	PEBB For DC-DC Converters
Partners	IPT, UNIOVI, FRENETIC, IFAT, ETHZ
Modelling	
The target is to combine equation-based models; finite element analysis-based models; and data-based models. Specifically, machine learning methods will the used for the optimization of magnetics (inductors, high frequency transformers).	

Limit of today's modelling:	State-of-the-art electromagnetic modelling of multichip power modules relies on extracting simplified equivalent R-L networks. However, these models lack the precision needed to accurately assess circuit stability and switching transients, which are critical for estimating switching losses. Additionally, the variation in device characteristics of SiC power MOSFETs has yet to be fully considered in the design of multichip power modules.
Target of improving modelling:	The design of multi-chip power modules is significantly influenced by factors such as current sharing, gate drive strategies, and the electromagnetic performance of the layout. The multi-domain simulation platform being developed by ETHZ will benefit both industry and academia by enabling faster prototyping and supporting the education of future experts. This comprehensive modelling framework will facilitate the classification of SiC power MOSFET dies for multichip power module design. Its goal is to address key challenges, including the suppression of transient current imbalances and the mitigation of unstable oscillations in parallel-connected SiC MOSFETs.
Summary of results	
We have proved the feasibility of electromagnetic (EM) modelling of a real-world example consisting of a printed circuit board designed for a double pulse test setup with two power modules mounted on it for dynamic characterization. A virtual twin is finally built including the frequency-dependent system behaviour, multiple dies and modules in parallel, and process-related parameter variability of SiC power MOSFET dies, which all allow simulating dynamic device operation with an enhanced accuracy. A close collaboration with ANSYS has been continued on the power semiconductor device optimization coupling Synopsys TCAD with Ansys OptiSLang for adaptive machine learning.	

TABLE 13

5.1.3 UC 1.4 BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage

Use Case	BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage
Partners	SCANIA, KTH, ALSTOM, RISE, IFAG, SAL
Modeling Assessment	
"Develop and implement models at both the system level (e.g., inverter) and the component level (e.g., MOSFETs, capacitors, etc.). Focus on developing electro-thermo-mechanical models for state-of-the-art power modules. Use these models to analyse the effects of various loading conditions on failure mechanisms that lead to degradation. Validate the models through accelerated test methods developed in Subtask 2.1.1.1 and assess the functionality of failure indicators as outlined in Subtask 2.1.1.2. Additionally, develop and apply mixed-mode TCAD models, incorporating thermal modelling and the extraction of electrical parasitic parameters, for SiC power modules in heavy-duty vehicle applications. Evaluate their reliability and robustness. Construct physics-based reliability models informed by simulations and experimental results.	
Limit of today's reliability assessment:	Thermal models for advanced packages, such as double-sided cooled packages, are currently underdeveloped. Moreover, new failure mechanisms emerging with advancements in packaging technology need

	to be modelled as part of this task. Additionally, a comprehensive electro-thermo-mechanical model of the system is lacking and should be developed to enable effective implementation in Digital Twins.
Target of improving reliability assessment:	Develop effective models for designing and developing next-generation drive inverters, considering various inverter topologies, voltage levels, cooling systems, and other factors. These models should combine physics-of-failure approaches and machine learning techniques, leveraging data collected from a wide range of vehicles operating daily and connected to a cloud-based data collection centre.
Summary of results	
A virtual-prototyping framework combining analytical loss modeling and electro-thermal coupling was developed for the 1200 V BEHDV traction inverter. The model quantifies the effect of die area and switching frequency on inverter efficiency and thermal behavior, identifying an optimal region around 300 mm² and 14 kHz for 2 kV SiC modules. Preliminary comparisons with datasheet data show agreement within ±5 %, and calorimetric validation is in preparation. The results establish a digital design foundation for reliability analysis and Digital-Twin integration within PowerizeD.	

TABLE 14.

5.1.4 UC 1.5 FCEV- Fuel Cell and Powertrain Inverter

Use Case	*FCEV-Fuel Cell and PT Inverter*
Partners	MBAG, RB, TUDO, FhG, ANS, IMEC, MATE, SAD, ETHZ, EDR, V2V
Modelling Assessment	
Developing electro-thermal and thermo-mechanical models for state-of-the-art power modules is a crucial step in predicting robustness and reliability. In this use case, models are created from the chip level up to the system level. Our goal is to develop models for power semiconductor power modules and, ultimately, for inverters that: 1. **Account for electro-thermal coupling**, including non-uniform temperatures and currents throughout the device. These models will be capable of predicting thermal runaway, thus providing a critical basis for maintaining operation within the safe range. The models will be calibrated and validated using destructive measurement results. 2. **Address coupled electro-thermal and thermomechanical loading conditions.** Evaluating stress and strain is a major challenge in current modelling approaches, due to the highly nonlinear, temperature-dependent behaviour of materials.	
Limit of today's reliability assessment:	Currently, finite element simulations at both the system and component levels are commonly used as part of reliability assessments. However, these simulations require significant computational power and time, limiting their use to a small number of designs. They also cannot be applied during operation. A compact digital twin appears to be a promising solution. In PowerizeD, Use Case 5, we aim to enhance compact digital twin technology by developing specific nonlinear metamodels for electro-thermal-thermomechanical behaviour of inverters and their components, including temperature dependence.

Target of improving reliability assessment:	For use during operation, we are creating reduced models that can be calculated on low-computational platforms, such as microcontrollers, for in-vehicle applications. By predicting the operating state and safe operating range, these models enable better utilization of components without compromising reliability. However, we also need to assess direct, damage-relevant quantities such as stress and strain. To address this, we plan to expand the application of artificial intelligence and machine learning techniques.

Summary of results

Multi-Chip Power Package with iForce Sensor

Conferences

A. V. Panchwagh, P. J. Gromala, S. Rzepka and B. Wunderle, "Verification of Material Models of an Epoxy Mold Compound Used in Power Module," *2025 26th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, Utrecht, Netherlands, 2025, pp. 1-8, doi: 10.1109/EuroSimE65125.2025.11006604.

Validation Study

It was observed that the FE-model could successfully capture the trends observed during experiments for both warpages, as well as stresses on the piezoresistive stress sensor, thus qualitatively validating the model.

Al-Wire Bond Parametric Geometry and Material Modelling with Gel

Global and sub-modelling comparison

- Evaluated plastic strain at the wire bond heel by comparing the full reference model with the sub model driven by displacements extracted from two global models: (a) global model with a linear material wire bond and (b) global model without the wire bond.
- The global–sub modeling approach reproduced the plastic-strain evolution in the heel region very closely to the reference model, indicating fidelity of the reduced/localized analysis.
- The global–sub model workflow delivered substantial computational savings versus the full reference run, enabling faster iteration while preserving the key local response metrics.

Comparison of ANSYS and COMSOL results

- Performed initial comparison of simulations using equivalent geometry and loading in ANSYS and COMSOL.
- The ANSYS model used a finer mesh with a limited number of sub steps to manage computational time, while the COMSOL model employed a coarser mesh.
- The COMSOL results exhibited a slightly stiffer response relative to ANSYS, consistent with the coarser mesh; this indicates that mesh and time-stepping choices influence the simulation results and harmonized comparison is being performed by transferring mesh from ANSYS to COMSOL.

Thermo-mechanical simulation model of THT solder of a Foil Capacitor

CTE measurements using DIC

- In plane strain fields were converted to thermal expansion and the gradient of this thermal expansion over temperature results in CTE of the material under study.
- From the thermal expansions were able tell if the material has same CTE over temperature (E.g. Core) or if there is a glass transition temperature associated to the material (E.g. Potting).

Material	CTE (ppm) ALONG DIAGONAL	CTE (ppm) UNDER AREA
Core	41.62	41.62
Potting	54.97 (CTE1)	58 (CTE1)
Potting	95.62 (CTE2)	108 (CTE2)

- The measured CTE values were used in simulation model and validated against in plane deformation of the whole capacitor measured using DIC

Global-local approach

- Global-model simulations are complete, and results are available. The newly measured and characterized foil-capacitors have been incorporated into the building-block assembly.
- The global–local workflow is currently in progress: displacement fields and boundary conditions will be transferred from the global/building-block models to the high-fidelity Sub model

TABLE 15.

5.1.5 UC 1.6b Medium Power Modular Stationary Charger

Use Case	Medium Power Modular Stationary Charger
Partners	ELC, UNIBO, SERI, IFI, IFAG, IFAT, FPG, HEPO, ETHZ, KEMP
Modelling	
	Experimentally-calibrated accurate models will be developed at both device and system levels in order to optimize the layout of each subsystem within the charging infrastructure. A dynamic average-value model will be considered to achieve an optimal compromise between computational costs of system-level analysis and the accuracy of the results.
Summary of results	
Electromagnetic (EM) modelling of the SiC-based Intelligent Power Module integrated in the DC/DC converter during the switching behavior. Estimation of the parasitic parameters and frequency-dependent effects have been carried out too. Virtual twin has been developed, including frequency-dependent system behavior multiple dies in parallel, and gate driver parameters, which all allow simulating dynamic device operation.	

5.1.6 UC 1.6c Large Power Stationary Charger

Use Case	Large Power Stationary Charger
Partners	PRE, VSL, TUDE
Modelling	
Summary of results	
Results of a data driven lifetime prediction of SiC MOSFETs is discussed in CDT1.1 (reliability) in section **4.1.4**. Furthermore, the loss and temperature model based digital twin of 30 kW phase shift full bridge converter, and 25 kW dual active bridge is discussed in CDT1.3 (Digital twins) in section **6.1.7**.	

TABLE 16.

5.1.7 UC 2.1 Flow battery power electronics

Use Case	UC 2.1 Flow battery power electronics
Partners	AQUA, TUDE
Modelling	
	Modelling of the Dual Active Bridge (DAB) converter analytically in Python to evaluate power losses, thermal stress and reliability of the converter. The model uses Rainflow counting, Monte Carlo analysis, Miner's rule, and the CIPS switch reliability model to evaluate the reliability of various devices, which are then used to evaluate the converter. An alternate model was developed in PLECS to simulate the DAB converter
Summary of results	
– Optimized loss-based design of the Dual active Bridge is developed, and two papers are presented in international conference: *S. Singh, J. Zeilstra, A. Shekhar and P. Bauer, "Optimal design methodology for Dual Active Bridge for Flow battery application," IECON 2024 - 50th Annual Conference of the IEEE Industrial Electronics Society, Chicago, IL, USA, 2024, pp. 1-5, doi: 10.1109/IECON55916.2024.10905263.* *S. Singh, J. Zeilstra, A. Shekhar and P. Bauer, "End of life influencing factors for Dual Active Bridge components in Flow Battery Application," 2024 IEEE 21st International Power Electronics and Motion Control Conference (PEMC), Pilsen, Czech Republic, 2024, pp. 1-6, doi: 10.1109/PEMC61721.2024.10726333.* – A flow battery model is developed based on measured stack data to be implemented as digital twin (CDT1.3) and reliability testing of dual active bridge (CDT1.1)	

TABLE 17.

5.1.8 UC 2.3 LED-Driver and LV DC Distribution Grid

Use Case	LED Driver and LV DC Distribution Grid
Partners	SIGN, TUDE, PLEXIM
CDT 1.2 Modelling / CDT 1.3 Digital Twin	
To calculate the cumulative failures of its LED drivers as function of time, Signify uses a proprietary Electronic Reliability Tool (ERT). The first input for the ERT is the Bill of Material (BoM) of the LED driver. For each component in the BoM the rated and used electrical stresses, and the nominal	

component temperature are specified. The second input of the ERT is the actual mission profile which contains information on the number of switches, surges and the actual case temperature. Currently the ERT applies a linear scaling of the nominal component temperatures to obtain the average actual component temperatures. Goal of the work done in CDT1.2 and CDT1.3 is to transform the ERT in a more accurate digital twin of a LED driver.
Summary of results
The updates on the Electronic Reliability Tool (ERT) resulted in a more accurate lifetime prediction. The improved data logging improves failure analysis and RuL estimation.

TABLE 18.

5.1.9 UC 3.1a Prognostics for industrial Drives.

Use Case	Prognostics for industrial Drives
Partners	ABB, BME, AALTO
Reliability Assessment	
In situ prognostics and health management (PHM) are key features in next generation industrial power converter designs to meet future reliability, sustainability, and lifecycle management requirements in demanding applications: 1) cyclic applications (thermomechanical degradation), and 2) corrosive gas (electrochemical migration) environments. 1) Limited demonstrations for PHM have been seen with existing sensors in industrial power converter applications, primarily concentrating on thermomechanical failure mechanisms; however, due to the lack of proper sensors and signals dedicated for prognostics and lack of in-situ computing speeds in embedded systems have hindered productization in large scale. Existing thermomechanical prognostics have been dees drop, the latter of which can be realized only in laboratory conditions with no simple way to be applied in existing industrial power converter applications. With these sensors only a limited prognostics of the remaining useful life (RUL) model can be developed and different failure mechanism (or degraded interfaces) in thermomechanical failures can be determined. However, a separation of failure mechanisms is not possible. 2) Currently there are no useful sensors, that could be used for RUL modelling of equipment in corrosive environments for power semiconductors. Commonly Cu/Ag coupons are used for estimating corrosion class in accordance with ISA 71.04-2013 or ISO9223 standards, however, these coupons are not economic for in-situ monitoring in industrial converters. -> Corrosion sensor topic was cancelled since after project start it became evident that the commercial sensors have developed so rapidly that there is no use to concentrate on this topic.	
Limit of today's reliability assessment:	Limited demonstrations for prognostics and health management PHM) have been seen with existing sensors in industrial power converter applications, primarily concentrating on thermomechanical failure mechanisms; however, due to the lack of proper sensors and signals dedicated for prognostics and lack of in-situ computing speeds in embedded systems have hindered productization in large scale. Existing thermomechanical prognostics have no simple way to be applied in existing industrial power converter applications. Thus, only a limited prognostics of the remaining useful life (RUL) model can be developed and different failure mechanism (or degraded interfaces) in

	thermomechanical failures can be determined. However, a separation of failure mechanisms is not possible.
Target of improving reliability assessment:	Improved accuracy of the junction temperature estimation by 50% compared to a State-of-the-Art module. Improved RUL estimation accuracy of 80 %. Next to the added sensing capabilities the development of reliable RUL model which can be used to determine thermomechanical and electrochemical migration induced failure mechanisms. While in CDT1.1 the on-chip junction temperature (T_j) monitoring in power semiconductor chips (e.g., Si-IGBT or SiC-MOSFET) will be demonstrated in existing EconoDUAL 3, in CDT1.2 the possible degrading parameters are to be added to the compact thermal model that will be iteratively compared with the measurements.
Summary of results	
Simulation showed uneven chip temperatures (141 °C max, 108 °C min) caused by voltage drops and current imbalance. In another case, variable TIM conductivity yielded higher overall chip temperatures up to 153 °C with a simulated 121 °C matching well to measured 114–117 °C. Results indicate chip temperatures depend strongly on TIM modelling; neglecting baseplate compression may underestimate central conduction and overpredict temperatures. The digital twin also highlighted the temperature elevation on the wires, which is confirmed by the measurements. In transient, the model showed good convergence when voltage load was applied while for current load, the model requires that further monitoring points must be added. Based on the temperature elevation in transient mode, the structure function of the module is determined where each part of the module along the heat flow path can be clearly distinguished.	

TABLE 19.

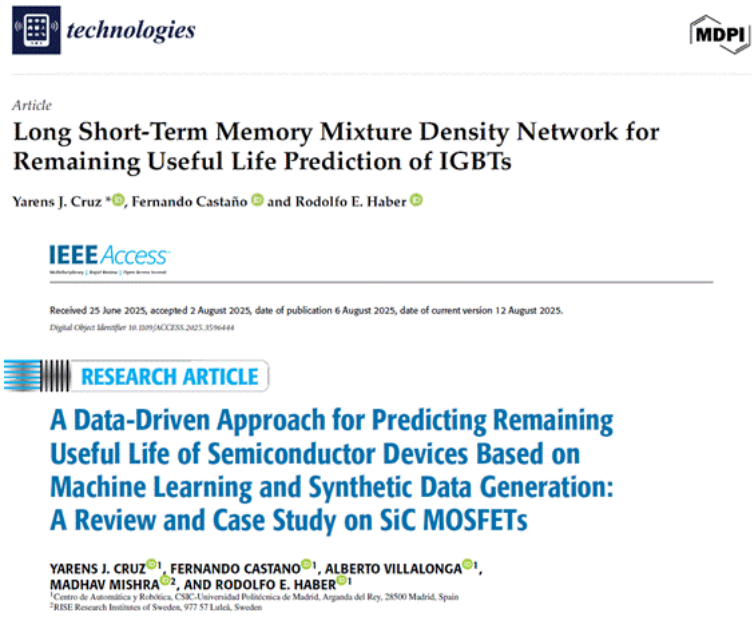
5.1.10 UC 3.2 New hyper-sensorised digital drive

Use Case	New hyper-sensorised digital drive
Modeling	
Modelling of electro-thermal models developed by PSC is performed to analyse various machine operating cycles provided by FAGOR for different types of machine tools. The results of these analyses will help verify the correct operation of each machine under its specific cycles. The resulting thermal stresses can also serve as input data for a framework developed by CSIC, which includes meta-modelling strategies for assessing the remaining useful life (RUL) of certain electromechanical components under different duty cycles.	
Limit of today's reliability assessment:	FAGOR's current product modelling remains incomplete, as it lacks integration of AI-based techniques. This shortfall affects the representation of product behaviour and limits the development of data-driven models. Moreover, there is no established strategy to quantify uncertainty in model predictions, further constraining the reliability and applicability of these models. To address modelling, several key AI methods have been selected based on state-of-the-art practices, real-time requirements, and desired

	performance. Specifically, Gaussian Process Regression (GPR) and Long Short-Term Memory (LSTM) are considered for few-shot learning, with XGBoost (decision trees) also under review. For transfer learning, the combination of LSTM and Mixture Density Networks (LSTM + MDN) is deemed the most suitable approach. Finally, all four topologies (GPR, LSTM, XGBoost, and LSTM + MDN) will be evaluated for potential metamodeling implementations.
Target of improving model:	In order to improve models of IGBTs and capacitors of FAGOR power drive, key AI techniques are selected according to the state-of-the-art, real-time constraints and required behaviour. Specifically, several recurrent neural networks topologies (i.e., RNN, GRU, LSTM, Bi-LSTM) are selected given their capabilities for modelling the temporal aspects of the degradation of electronic components. On the other hand, Mixture Density Networks (MDN) are selected for their ability for representing uncertainty on the underlying data, so they are adequate for few shot learning scenarios where quantification of the uncertainty is extremely useful. Additionally, combination of the previous topologies can simultaneously tackle several modelling aspects. Also, transfer learning approaches can speed up the creation or update of accurate models. Moreover, metamodeling approaches can help correct the mistakes produced by individual models resulting in more robust predictions. Finally, since all these approaches are data-driven, the internal data collected for training them can be used for detecting hardware improvement opportunities.
Summary of results	

A framework for modelling and predicting RUL of power electronic components.

2 papers published.



technologies

MDPI

Article

Long Short-Term Memory Mixture Density Network for Remaining Useful Life Prediction of IGBTs

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RESEARCH ARTICLE

A Data-Driven Approach for Predicting Remaining Useful Life of Semiconductor Devices Based on Machine Learning and Synthetic Data Generation: A Review and Case Study on SiC MOSFETs

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1 software registered

TABLE 20.

6 CDT 1.3 Digital Twins (Task Lead – ANSYS)

The goal of a Digital Twin is to improve real-world entities and processes through its virtual representation. Digital Twins can be used either directly or indirectly (with more human interaction) to steer real-world entities and processes.

The development of Digital Twins heavily relies on information derived from simulations. However, the detailed simulation models often operate far from real-time when compared to the dynamics of real-world entities and processes. To enable direct interaction, a hardware-in-the-loop approach combined with compact metamodels (or Reduced Order Models, ROMs) generated from simulations and experiments using AI/ML (Artificial Intelligence/Machine Learning) is ideal. Digital Twins based on such metamodels are referred to as Compact Digital Twins.

Digital Twins are set to become essential building blocks for the digitization of power electronics. In the PowerizeD project, we refine the concept of the Digital Twin to enhance collaboration along the value chain, enabling the secure exchange of critical information while keeping intellectual property (IP) confidential. Typical applications include Fault-Tolerant Converters and Reconfigurable Hybrid AC-DC Links. Many of the project's use cases aim to realize at least some functionality of a Digital Twin.

Digital Twins can be used for runtime optimization and/or for improving product reliability (as discussed in CDT 1.1). For reliability purposes, fragility surfaces—metamodels of failure probabilities—are particularly useful. These fragility surfaces provide insights into system vulnerabilities and allow us to envision systems that are antifragile. Antifragile systems, as defined by Nassim Nicholas Taleb around 2012 (https://en.wikipedia.org/wiki/Antifragility), have the ability to learn and improve under stress, load, or other challenging conditions.

The workflow below outlines a draft of an antifragile system leveraging fragility surfaces (metamodels of failure probabilities) to create systems that not only adapt to stress but also improve in response to it.

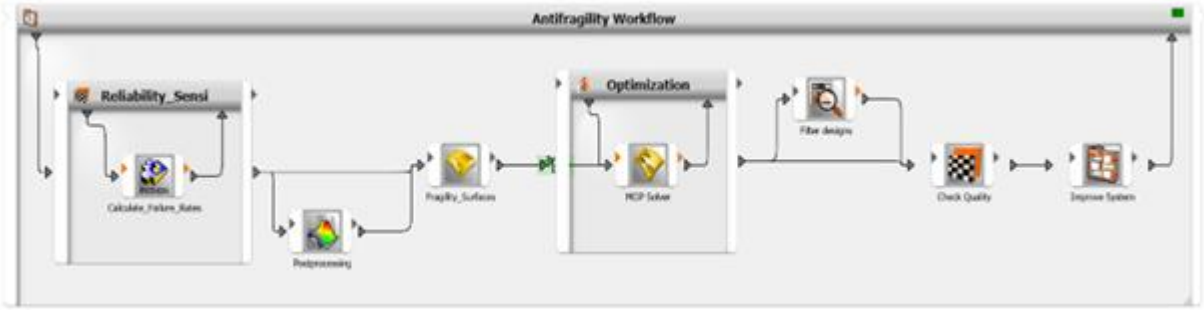

FIGURE 2.

This workflow processes data from real-world entities and uses it for simulations to refine the metamodels. It helps determine where the real-world entity is positioned within the parameter space and how far it is from critical areas (e.g., failures). With updated information, the system can optimize its positioning. Quality checks are incorporated to evaluate proposed improvements before they are finalized.

This workflow essentially represents a learning system. In all PowerizeD use cases, the block labeled **Reliability_Sensi** cannot operate in real time. Therefore, it must be separated from the Compact Digital Twin, which can be implemented on-board and updated through external mechanisms. The second

part of the workflow, starting with the **Fragility Surfaces**, holds significant potential for on-board implementation. Self-learning systems are a long-term goal, but initial steps in this direction are essential and beneficial.

To develop a Digital Twin, the following steps are planned and discussed

a) Definition of Requirements for the Digital Twin

- Determine the purpose of the Digital Twin.
- Define requirements from the customer (e.g., operating hours, ambient temperatures, load profiles).

b) Analysis of Physical Failure Modes

- Define failures (e.g., solder point cracks, die and wire bond delamination).
- Assess the physical effects of these failures.

c) Definition of Simulation Models

- Develop models such as FEM simulations, system simulations, and analytical models.
- Calibrate models and identify parameters.

d) Development of Metamodels

- Conduct DoE-based simulation runs.
- Perform sensitivity analysis, optimization, and robustness evaluation (Robust Design Optimization, RDO).
- Develop fragility surfaces.

e) Connect Metamodels to a Digital Twin (FMU/FMI)

- Integrate metamodels into system simulations.
- Acquire sensor data.
- Enable physical health management and system reactions.

f) Implementation into the Demonstrator for Specific Use Cases

- Apply the Digital Twin in demonstrators tailored to specific use cases.

Within the first half of the projects mainly the steps a) to d) have been in the focus, within the second half the steps e) and f) have been finalized.

In the tables below the status of the integration of digital twins by end of the project is described.

6.1.1 UC 1.1 Railway Propulsion Systems

Use Case	Railway Propulsion Systems
Partners	ALSTOM, KTH, EDRM
CDT 1.3 Digital Twin	
Development of a thermal digital twin. Develop hybrid physical-AI thermal model to accurately relate measured power semiconductor module temperature to an actual junction temperature.	
Description how the digital twin will be demonstrated	New power semiconductor modules for railway traction include embedded temperature sensors which allows a closer monitoring of the junction temperature. However, the relation to the actual junction location needs to be considered to estimate the actual junction temperature. By creating a digital twin that consists of physics based and data driven modelling calibrated for a specific component the thermal behaviour can be predicted

	with a resulting accurate junction temperature estimation for control and health monitoring purposes.
Summary of results	
Key results include a number of ROMs with different degrees of speed, accuracy, and number of outputs that can predict temperature in critical areas of power module based on actual duty cycle	

TABLE 21.

6.1.2 UC 1.2 PEBB For Traction Converters

Use Case	PEBB For Traction Converters
Partners	IPT, UNIOVI
CDT 1.3 Digital twins	
The target is to obtain an optimal design for a busbar in terms of low stray inductance for a traction converter, complying mechanical, electrical and thermal constraints.	
Limit of today's Digital twins:	The design of a busbar today relies heavily on multiple simulations using multi-physics models. However, integrating all design constraints into a single simulation remains challenging. As a result, different software environments are often required to evaluate these constraints separately. This lack of integration leads to suboptimal designs.
Target of improving Digital twins:	To address this, a digital twin can be employed to create a comprehensive metamodel of a busbar. This metamodel would consider mechanical constraints (e.g., maximum dimensions, bending radius), electrical constraints (e.g., creepage distance, clearance distance), and thermal constraints (e.g., maximum terminal temperature, dielectric temperature limits). By incorporating these factors into a unified simulation environment, the design process can optimize stray inductance while adhering to all necessary constraints. This approach would significantly reduce design time and enable optimal designs, ultimately increasing the maximum current capacity of the Power Electronic Building Block (PEBB).
Summary of results	
• *Hybrid PSO-IPM* algorithm for digital twin parameter identification provides consistently good results. • *IPM* gradient-based algorithm can provide better accuracy, however, it needs effective updating of initial guess for resistive elements. Including compensation of sensor errors in the optimization is crucial; including thermal measurements helps to improve the estimation of internal resistances of power devices and inductors. • *Multi-start* strategies can offer improved robustness but have high computational cost making them unsuitable for real-time applications. Accuracy of parameter identification achieved using the developed synchronous sampling technique is proved to be comparable to HF technique. This avoids using HF sensors and acquisition system that could be prohibitive in industrial applications.	

TABLE 21.

6.1.3 UC 1.3 PEBB For DC-DC Converters

Use Case	PEBB For DC-DC Converters
Partners	IPT, UNIOVI, FRENETIC, IFAT
CDT 1.3 Digital twins	
The target is twofold. Anomaly detection (reliability) and efficiency improvement	
Limit of today's Digital twins:	One major challenge is the limited accuracy in estimating the system state, coupled with implementation complexity. Many proposed digital twins for electronic power converters operate at high sampling rates, necessitating dedicated hardware. This additional hardware not only increases costs but can also introduce reliability concerns. Therefore, the ideal digital twin should operate on existing control hardware and require minimal resources.
Target of improving Digital twins:	In terms of anomaly detection, the digital twin should be capable of modelling the normal aging process of components (e.g., capacitors) and account for changes due to operating conditions such as temperature and load. It must detect deviations from expected behaviour to ensure system reliability. Regarding efficiency, the digital twin should provide real-time insights into energy consumption, enabling optimization of the system's operating point. This capability is particularly valuable in scenarios where trains are powered by battery systems, as it would enhance energy management and overall system performance.
Summary of results	
• The developed digital twin methodologies have been successfully applied to the constructed downscaled dc/dc converter prototypes and are proved to be directly extendable to other converter topologies. • Coordination with IPT to apply the developed methodologies on their full-scale dc/dc resonant converter has been carried out. Several experimental data sets captured from the demonstrator were analysed and processed for that purpose. • Digital twin health monitoring and predictive maintenance capabilities have been validated through simulation of component and sensor degradation, showing good accuracy in monitoring parameter variations of passives (L, C) and power switching devices ($R_{ds(ON)}$) across wide degradation ranges and varying operating conditions. • Parameter identification methodology has been enhanced to use synchronous sampling, and subsequent challenges have been addressed showing feasibility of the approach. Digital twin proposed methodologies have been verified under varying operating conditions; component degradation/aging; noise in measured signals and sensor errors.	

TABLE 22.

6.1.4 UC 1.4 BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage

Use Case	BEHDV (Battery Electric Heavy-Duty Vehicle) Drive Inverter for High Voltage
Partners	SCANIA, KTH, ALSTOM, RISE, IFAG, SAL, EDRM

CDT 1.3 Digital Twin
Estimate the life expectancy of a module based on operating conditions and varying duty cycles. Building on the work conducted in WP2.1.2 (modelling failure modes, behaviour, and degradation rates) and WP2.1.3.1 (developing compact, lightweight digital twins), this task focuses on applying the digital twin to a system (e.g., a converter) to estimate the module's lifespan under different operating scenarios. A predictive maintenance strategy will be developed using insights from the compact digital twin, field data, and lifetime estimation techniques. Digital Twin Development Progress: The back-to-back inverter model has been designed in ANSYS Q3D, and a lab prototype is completed. A loss model has been developed in MATLAB, incorporating dependencies on frequency, junction temperature, voltage, current, and phase shift. Using calorimetric and electrical loss measurements, feedback from the experimental setup is now being integrated to update and validate the ROM, improving the digital twin's accuracy.
Summary of results
High-fidelity and reduced order models of power modules in Ansys Icepak

Table 29.

6.1.5 UC 1.5 FCEV- Fuel Cell and Powertrain Inverter

Use Case 1.5	FCEV- Fuel Cell and Powertrain Inverter
Partners	MBAG, RB, TUDO, FhG, ANS, IMEC, MATE, SAD, ETHZ (Lead RB)
CDT 1.3 Digital Twin	
The goal is to develop a compact digital twin of the inverter system, based on metamodels derived from simulations of its components, including the MOSFET, DC-Link capacitor, and power module on the cooler.	
Physics of Failure	Solder Joint fatigue Wire Bond fatigue Die attach fatigue (solder or silver sinter)
Metamodel generation	Based on the models from CDT 1.2 and those developed for this use case, simulations are conducted using an appropriate Design of Experiment (DoE). Sensitivity analysis, optimization, and robustness analyses are then performed to establish suitable metamodels, including those incorporating failure probabilities.
Description how the digital twin will be demonstrated	Ideally, the Compact Digital Twin will be integrated into the Electronic Control Unit (ECU) that controls the inverter, enabling the avoidance of critical temperature ranges. To achieve this, the metamodels must ultimately be combined into a system simulation using FMU/FMI or a similar technique, interacting with sensors attached to the demonstrator.
Summary of results	
Digital Twin implementation in µC **Benchmarking summary:**	

- Random Forest: Achieved 80% accuracy initially; easy to train but has higher prediction time and large model size.
- LSTM/GRU: Harder to train with complex preprocessing; lower prediction time and smaller model size due to memory efficiency.
- Stochos–Gaussian Process: Accurate but complex for microcontroller implementation.
- Final Choice: Random Forest, optimized with additional features to achieve 97% accuracy.

KPIs

The accuracy of prediction based on test data is determined using R2 score (a statistical measure that represents the proportion of variance in the dependent variable that is explained by the independent variable(s) in a regression model) 0.0-1.0 (Bad and Good fit)

Model	***Objective***	***Metrics on test data***
Random Forest in loop	Volume averaged Acc. Plastic strain in sinter Values in range (0-0.02)	R2_score: 0.98

HPC: 192 CPUs → calculation time → $time_{FEM}$= 24554 sec (900 points)

Laptop: 1 CPU, 16 GB RAM, 256 GB SSD drive

Model	***Prediction time for 1 point in time***	***Calculation Speed Ratio***
Random Forest in loop	94 ms	272

C2000 Micro-controller: 1CPU, 512KB FLASH and 44KB RAM at 200MHz clock speed

Model	***Prediction time for 1 point in time***	***Calculation Speed Ratio***
Random Forest in loop	0.1 s	270

Comparison of Simulation (reference), prediction (laptop) and prediction (c2000 µC)

- Model validity on unseen data: Model accuracy was evaluated on test data (data not used for training) to assess generalization; simulation outputs were compared with the ML model predictions from the training PC and after deployment to the embedded device.
- Embedded implementation: Input-feature preprocessing and prediction post-processing were implemented in C for the microcontroller, enabling on-device inference with the same feature pipeline used during development.
- Deployment parity: Predictions from the trained model on the PC and the embedded device were effectively identical, demonstrating successful model translation and numerical consistency after flashing to the target hardware.
- Next steps toward field use: The implementation is ready to accept real-world inputs — the current simulated temperature input will be replaced by measured temperatures from the NTC sensor in the power module during operation to enable live monitoring and prediction.

Solder Joint Fatigue - H-PSOF-8L (Infineon)

We are now able to estimate for example the remaining useful lifetimes by applying techniques from robust design optimization to electronic components in a very flexible way giving new possibilities for Prognostics & Health Management. Also, we are now able to include different usage

models for an improved adaptation of the estimation of the remaining useful lifetime. This makes it possible to create workflows derived from high quality meta-models that can run in future on embedded software enabling also self-learning features.

TABLE 23.

6.1.6 UC 1.6b Medium Power Modular Stationary Charger

Use Case	Medium Power Modular Stationary Charger
Partners	ELC, UNIBO, SERI, IFI, IFAG, IFAT, FPG, HEPO, ETHZ, KEMP, ANS, PLEXIM
CDT 1.3 Digital Twin	
Digital twin is necessary to define the optimal modular architecture of the EV charging system.	
Description how the digital twin will be demonstrated	Digital twin should be implemented according to the system and devices specifications and should have the same behaviour of the real system.
Summary of results	
The sensitivity analysis allows to better understand the design space, the influence of the different input parameters. Moreover, based on the metamodels, it is possible to select appropriate configurations and implement adequate steering mechanisms that are helpful during DAB converter operations, for example avoiding high junction temperatures and thereby increasing lifetime.	

TABLE 24.

6.1.7 UC 1.6c Large Power Stationary Charger

Use Case	Large Power Stationary Charger
Partners	PRE, VSL, TUDE
Digital Twin	
Summary of results	
– Digital twin of 30 kW phase shift full bridge converter is prepared and its efficiency is compared with measurements of a similar prototype. The accuracy of digital twin results is above 98 %. – Digital twin of 25 kW dual active bridge is prepared. Its simulated component losses, temperature and efficiency is presented.	

TABLE 25.

6.1.8 UC1.7 System of Systems

Use Case	System of Systems
Partners	OTH, EDI, UNIBO, HUA, PLEXIM, ANSYS
CDT 1.3 Digital Twin	
A digital twin of battery electric vehicles is needed to develop a machine learning model for estimating the remaining useful life (RUL) of lithium-ion batteries and to validate its functionality and accuracy. The aim is to estimate the RUL of EV batteries. A digital twin of vehicular scenarios is also needed to develop intelligent routing algorithms for EVs.	
Description how the digital twin will be demonstrated	The digital twin is used to simulate several different battery electric vehicles with different driving profiles to which the RUL estimation model is applied to validate it. To do this, it is necessary to combine a vehicle model and a battery ageing model. This is achieved by combining simplified battery and vehicle meta-models, for example using FMU/FMI

	or similar techniques, to simulate the interaction between driving profile and battery ageing. Ideally, the digital twins and RUL estimation are resource efficient enough to be integrated on edge platforms. Furthermore, the digital twin of vehicular scenarios will be demonstrated in combination with EV routing.
Summary of results	
1. The performance of the drive unit model has been increased allowing a simulation of a 30-minute drive cycle within 4 seconds significantly reducing calculation costs. 2. The PyBaMM simulation allowed us to generate extensive battery ageing data sets under realistic load conditions tackling the problem of generating expensive real-world data. However numerical problems remain allowing the simulation with sufficient ageing only within a limited parameter range. 3. Based on the simulated data, a efficient meta model with battery ageing has been developed allowing to break down the simulation of a battery life cycle to a few hours instead of several years. This model has been coupled with the developed drive unit model allowing the modelling of a whole electric vehicle and running test drives within seconds. The data from this EV is further used in a federated learning system for estimating the battery's remaining useful lifetime.	

Table 32.

6.1.9 UC 2.1 Flow battery power electronics

Use Case	UC 2.1 Flow battery power electronics
Partners	AQUA, TUDE
Modelling	
	Modelling of the Dual Active Bridge (DAB) converter analytically in Python to evaluate power losses, thermal stress and reliability of the converter. The model uses Rainflow counting, Monte Carlo analysis, Miner's rule, and the CIPS switch reliability model to evaluate the reliability of various devices, which are then used to evaluate the converter. An alternate model was developed in PLECS to simulate the DAB converter
Summary of results	
A real time digital twin of a high voltage (600 V) flow battery was implemented and experimental data for charge/discharge emulation with 3.3 A constant load current is obtained.	

Table 33.

6.1.10 UC 2.3 LED-Driver and LV DC Distribution Grid

Use Case	LED Driver and LV DC Distribution Grid
Partners	SIGN, TUDE, PLEXIM
CDT 1.2 Modelling / CDT 1.3 Digital Twin	
To calculate the cumulative failures of its LED drivers as function of time, Signify uses a proprietary Electronic Reliability Tool (ERT). The first input for the ERT is the Bill of Material (BoM) of the LED driver. For each component in the BoM the rated and used electrical stresses, and the nominal component temperature are specified. The second input of the ERT is the actual mission profile which contains information on the number of switches, surges and the actual case temperature. Currently the ERT applies a linear scaling of the nominal component	

temperatures to obtain the average actual component temperatures. Goal of the work done in CDT1.2 and CDT1.3 is to transform the ERT in a more accurate digital twin of a LED driver.
Key results
The updates on the Electronic Reliability Tool (ERT) resulted in a more accurate lifetime prediction. The improved data logging improves failure analysis and RuL estimation.

Table 34.

6.1.10.1 UC 3.3 New hyper-sensorised digital drive

Implementing a digital twin is key step for UC 3.3. By creating a digital twin of the entire system, it becomes possible to anticipate and prevent unscheduled machine shutdowns. To support these capabilities, a dedicated hardware platform is being developed that can run real-time or Hardware-in-the-Loop (HIL) simulations.

When the final design is completed—potentially including Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and HIL phases—a prototype will be constructed. This prototype will be extensively instrumented to validate the models and generate a simplified digital twin that can operate in the CNC at runtime. In this setup, virtual sensors will help prevent components from working outside their intended ranges, while centralized databases will collect and store the resulting data.

The core innovation lies in the development of advanced modulation techniques grounded in multi-objective optimization of key performance metrics. By optimizing factors such as voltage and current Total Harmonic Distortion (THD), leakage current, voltage derivatives, and electromagnetic and acoustic noise—as well as common-mode interference—these techniques aim to maximize overall system performance.

Use Case	UC 3.2 New hyper-sensorised digital drive
Partners	Fagor, CSIC, PSC
CDT 1.3 Digital Twin (DT)	
A Digital Twin (DT) represents a state-of-the-art method for emulating systems through mathematical models and hardware acceleration. This concept has been applied to FAGOR converters, enabling the creation of a highly accurate real-time replica of their systems. The DT serves as a real-time emulator closely matching the behaviour of actual converters by relying on electro, mechanical, and thermal models. It will respond with the same magnitude and timing as the physical system, making it possible to check, validate, and optimize both the converters and their control stages. As a result, the DT functions as a powerful tool for enhancing reliability. The DT also plays a critical role in contingency planning by allowing engineers to identify and anticipate potential issues that could harm or damage the real converter—enabling corrective actions before any physical impact occurs. Currently, FAGOR's product reliability is assured through the HALT-HASS methodology, which involves destroying physical products during testing. However, by leveraging a virtual environment, the DT can conduct these "destructive" tests without causing permanent damage or financial loss. This approach offers an effective alternative to traditional HALT-HASS practices.	
Description how the digital twin will be demonstrated	The Digital Twin (DT) will be embedded in a System on Chip (SoC) and connected to a computer, enabling real-time visualization of the internal waveforms generated during emulation. To validate its performance, the DT will be demonstrated in various test scenarios alongside actual FAGOR prototypes, allowing engineers to compare the DT-generated waveforms with those of the physical system. It is important to note that

	the DT is a standalone system capable of operating independently from the real converters. This makes it an invaluable tool for testing, analysis, and optimization without requiring direct use of the physical hardware.

Summary of results

Highlight the key nuggets of your research in context

Transmission line physics and emulation models oriented to real time emulation has been one of the biggest study and research points in this reporting period. Taking into account in the models the reflected wave, the effect of parasitic grounding impedance and its effect in inductive loads (especially asynchronous motors) were critical aspects that reinforced the model accuracy.

SiC model lack of accuracy in the switching instant was tracked to the lack of emulation of the re-combinatory effects of the loads and of the charge movements between parasitic capacitances. Creating the extra expressions were not an issue but including those expressions in the models while maintain the very same time step represented a complex research activity.

Table 35.