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FASTEST

Fast-track hybrid testing platform for the development of battery systems

Deliverable D4.1: Safety and reliability AI-powered battery toolchain architecture and framework design.

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Project Abstract

Current methods to evaluate Li-ion batteries safety, performance, reliability and lifetime represent a remarkable resource consumption for the overall battery R&D process. The time or number of tests required, the expensive equipment and a generalized trial-error approach are determining factors, together with a lack of understanding of the complex multiscale and multi-physics phenomena in the battery system. Besides, testing facilities are operated locally, meaning that data management is handled directly in the facility, and that experimentation is done on one test bench.

The FASTEST project aims to develop and validate a fast-track testing platform able to deliver a strategy based on Design of Experiments (DoE) and robust testing results, combining multi-scale and multi-physics virtual and physical testing. This will enable an accelerated battery system R&D and more reliable, safer, and long-lasting battery system designs. The project's prototype of a fast-track hybrid testing platform aims for a new holistic and interconnected approach. From a global test facility perspective, additional services like smart DoE algorithms, virtualized benches, and DT data are incorporated into the daily facility operation to reach a new level of efficiency.

During the project, FASTEST consortium aims to develop up to TRL 6 the platform and its components: the optimal DoE strategies according to three different use cases (automotive, stationary, and off-road); two different cell chemistries, 3b and 4 solid-state (oxide polymer electrolyte); the development of a complete set of physic-based and data driven models able to substitute physical characterization experiments; and the overarching Digital Twin architecture managing the information flows, and the TRL6 proven and integrated prototype of the hybrid testing platform.

LIST OF ABBREVIATIONS, ACRONYMS AND DEFINITIONS

Acronym	Name
SoC	State of Charge
SoH	State of Health
SEI	Solid Electrolyte Interphase
P2D	Pseudo 2D
BMS	Battery Management System
MdT	Multi-domain Tool chain

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1. EXECUTIVE SUMMARY

The FASTEST project is an innovative initiative in battery technology that focuses on promoting sustainable progress through innovation. The objective is to enhance the effectiveness and safety of lithium-ion batteries by utilizing a cutting-edge fast-track hybrid testing platform, which also accelerates research and development. This innovative methodology integrates empirical testing with computational simulations, providing a sophisticated framework for evaluating the safety, dependability, and longevity of batteries.

There are general rules for the multi-domain tool chain (MdT) architecture in Deliverable 4.1. The FASTEST project will use this as a basis for modeling, integrating, and validating the safety and reliability tests in the battery model for the G3 and G4. The proposed tool will provide safety and reliability tests for the battery at cell and mudel levels, as defined in the WP1. Additionally, the WP3 will develop an interface with the aging model, enabling the application of safety and reliability tests to the battery across various SOHs. Then, there is a need to invest in the design and development of the tool chain in T4.2. Moreover, the WP5 will develop the proposed tool chain with DT to integrate it into the ongoing work of FMU and FMI. This integration will facilitate the deployment of safety and reliability tests from the physical test bench to the virtual environment, thereby reducing the time and cost of battery testing.

This deliverable will offer a thorough understanding of the tool chain's structure and its interactions with the aging model and DT, which will be crucial during the model development process. Moreover, we must define the internal interfaces between the test models for T4.3, which focuses on the integration and optimization of battery AI-powered multi-domain toolchain cells at the system level.

2. INTRODUCTION

The D4.1 begins with an overall assessment of the T4.1 position in the WP 4 and explains how the outcome of this task will serve as an input to the other tasks in the WPO4, providing further insight into the flow of activities in the WP 4 of the FASTEST project. Fig. 1 presents the comprehensive multidomain scheme that the project will utilize to conduct safety and reliability tests at a virtual battery installation. Mover, the green box, shows the base of the toll chain architecture, which will be invested within the framework of the D4.1.

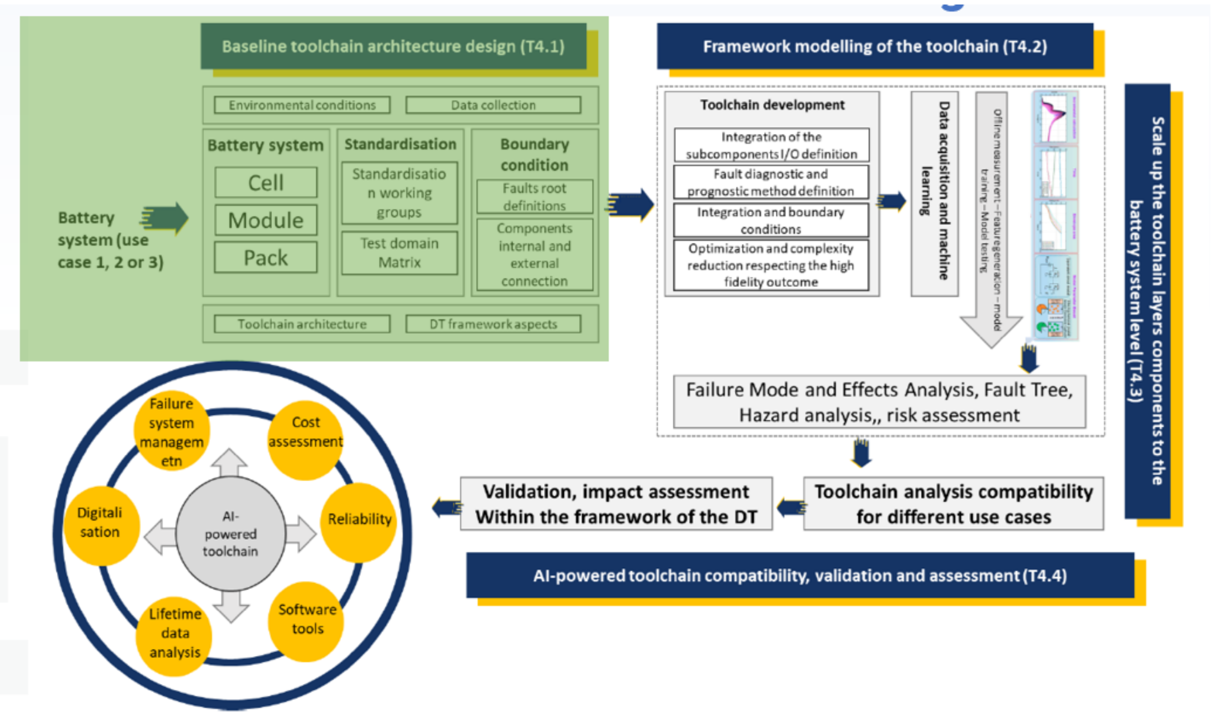


Figure 1 safety and reliability test tool of the FASTEST

Part one of the tool chain (T4.1) states that the tool will be able to test the cell's safety and reliability up to the system level (as part of the tool's functionality). The tool has the capability to test both G3 and G4 of the lithium-ion battery, making it suitable for use in all three scenarios within the FASTEST project: autonomous, off-road, and stationary. This domain needs to be taken into account in T4.2 and T4.3, which deal with the design, development, and integration of the test models.

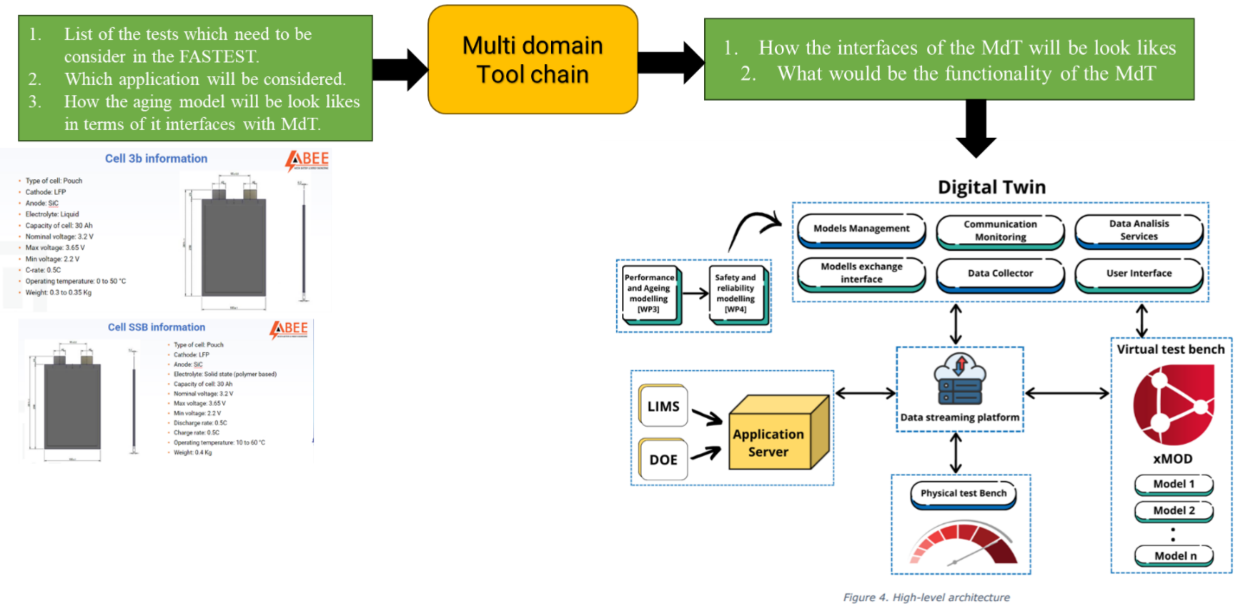
The interaction between the tool and the aging model in the WP3 and DT in the WP5 needs to be considered. Moving forward, the boundary condition in the internal communication of the test model will play a key role in improving the functionality and communication of the test model in the DT and with the physical test bench in the virtual testing procedure. Therefore, D4.1 will investigate the three main aspects to serve as a baseline for the design, development, and integration of the safety and reliability testing model within the tool's framework.

- The interaction between the aging model, which will be developed in the WP3, and MdT.
- The interaction between the DT, which will be developed in the WP5, and MdT.
- The internal bounding condition of the testing models and their interaction with the models to provide safety and reliability testing for batteries.

3. MdT instructions and requirements

3.1 MdT requirements

MdT provides virtual safety and reliability tests for the G 3 and G 4 after lithium and batteries, catering to three distinct applications: automated, stationary, and off-road. Figure 2 shows the MdT's position within the FASTEST project framework. The left side displays the data gathered from WP1, which includes the list of the tests and the domin (cell and system levels) required as inputs for the MdT. On the right side, you can see the model that will be developed in WP4 and integrated into the DT in WP5.



Cell 3b information

- Type of cell: Pouch
- Cathode: LFP
- Anode: SiC
- Electrolyte: Liquid
- Capacity of cell: 30 Ah
- Nominal voltage: 3.2 V
- Max voltage: 3.65 V
- Min voltage: 2.2 V
- C-rate: 0.5C
- Operating temperature: 0 to 50 °C
- Weight: 0.3 to 0.35 Kg

Cell SSB information

- Type of cell: Pouch
- Cathode: LFP
- Anode: SiC
- Electrolyte: Solid state (polymer based)
- Capacity of cell: 30 Ah
- Nominal voltage: 3.2 V
- Max voltage: 3.65 V
- Min voltage: 2.2 V
- Discharge rate: 0.5C
- Charge rate: 0.5C
- Operating temperature: 10 to 60 °C
- Weight: 0.4 Kg

Figure 2 MdT positioning within the framework of the fastest Project

3.2 MdT interaction

In order to understand the requirements for the baseline of the multidoment tool change, we need to see what the interaction between MdT with other tasks and WPs of the project would be. According to Fig. 3, there are serval interactions that need to be controlled at this stage of the WP4 activities. The relationship between

WP4 and WP1, between WP2 and WP3, and between WP4 and WP5 is evident. These interactions need to be considered during the modeling integration and validation of the MdT in the WP4. Here you can see the data gathered by WP1 in terms of the tests that need to be considered in the safety virtual testing demonstration, and then that will understand what kind of applications need to be considered for which domain for the cell or the system level.

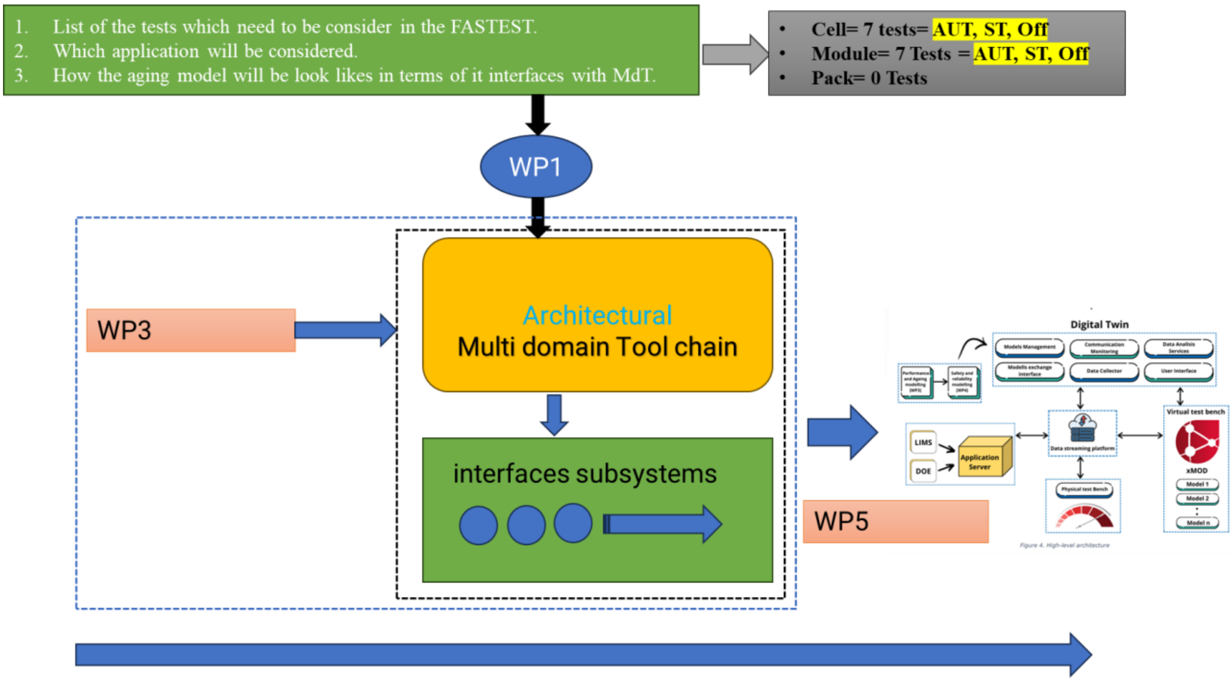


Figure 3 MdT interaction

All the necessary information from WP1, followed by its interaction with the aging and characterization models from WP3, has been given. The requirements regarding interfaces between the outcome of task 4.1 and the WP4 and WP5 during the integration with the digital twin also need to be considered.

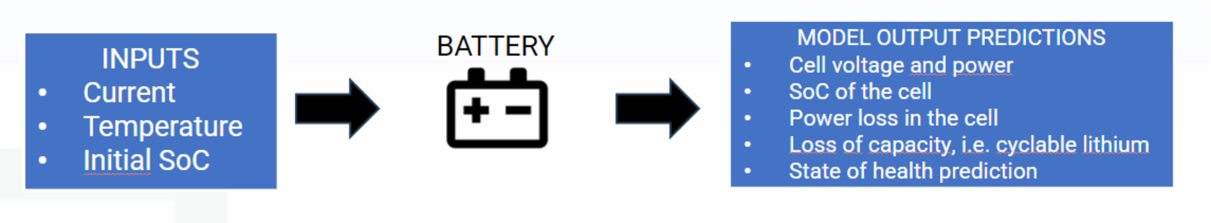
4. MdT and aging model

This section provides an overview of the architectural concepts of safety, reliability, and aging modeling by explaining the interactions (i.e., inputs and available outputs of the electrochemical battery model coupled with the aging model) with the MdT in a single battery cell configuration or at the system level, i.e., module/battery pack configuration with multiple batteries. The aim is to first understand and predict the behavior of the battery with the model by assessing its state of health (SoH). Then, based on the SoH prediction, a safety test can be deployed, e.g., with different currents, temperatures, etc.

4.1 Cell level

The basis for battery-related simulations is a physics- based electrochemical model inspired by the pioneering research of Newman et al. from 1975 [1] in the field of porous electrode theory. Current modern electrochemical models use the so-called pseudo-2D approach (P2D), which was introduced by Doyle et al. in 1993 [2]. The description of the electrochemical model, its governing equations and the coupling with thermal and degradation phenomena is described in detail in Deliverable D3.1

– Multiscale high fidelity modelling paradigm for physical testing virtualization of the FASTEST project. **Error! Reference source not found.** schematically shows t he possible inputs and outputs of the electrochemical model when modelling a single battery. The inputs include the current, the temperature and the initial state of charge of the battery. The current is generally a function of time and is fed into the battery model using the exchange rate prescribed in the online applications. The value of the current is determined by the sensors. Since the current sensors measure the current with a certain measurement error, the information about the state of charge (SoC) of the battery must be corrected with the SoC observers. The temperature of the cell is also an important input parameter for the electrochemical model, as the temperature has a profound influence on the rate of the chemical kinetics within the cell as well as on the transport and degradation phenomena. Of course, the electrochemical model must take into account the temperature dependence in the governing equations. This is usually done either with the Arrhenius approach or with experimental measurements.


INPUTS

- Current
- Temperature
- Initial SoC

BATTERY

MODEL OUTPUT PREDICTIONS

- Cell voltage and power
- SoC of the cell
- Power loss in the cell
- Loss of capacity, i.e. cyclable lithium
- State of health prediction

Figure 4 Inputs and outputs of the electrochemical model of a single battery.

At each time step, the electrochemical model can provide multiple output results that can be used for advanced battery monitoring, such as battery management system (BMS) or state of health (SoH) observers. The predicted voltage of the battery is the most important output of any battery model. In the case of electrochemical models, the resulting voltage is the potential difference between the cathode and anode potentials. The predicted power of the cell is simply a product of cell voltage and current. The predicted SoC of the cell in the electrochemical model is based on the integration of the lithium content in both electrodes (i.e. calculation of electrode stoichiometries) compared to the Coulomb counting in equivalent circuit models. As mentioned above, the model assumes that the input current is accurate, so corrections to the SoC may be required over time. The calculation of the power losses in the cell is composed of three contributions: irreversible losses due to reaction losses and ohmic losses, and reversible losses due to entropic changes in the electrodes. The information about the power losses is usually entered as input in 3D thermal models of the battery.

Over time and with an increasing number of cycles, the performance and capacity of the battery decreases. Appropriate application of degradation modelling is required to model capacity loss over time with reasonable accuracy. The capacity loss is directly related to the loss of cyclable lithium in the cell. This Li is involved in various side reactions that depend on the local concentrations within the cell, the potential and the temperature and cause the degradation of the battery. The most common side reactions are the growth of a passivated solid electrolyte interphase (SEI), the plating and reversible stripping of metallic Li on the anode particles, particle cracking, etc. and are also described in more detail in Deliverable D3.1. These ageing models consume cyclable lithium, and the amount of Li lost can be calculated by integrating the ageing-induced molar fluxes over time. Based on the amount of lost cyclable Li, the SoH value of a battery can be predicted.

4.2 System level

At the system level of the battery module/battery pack, several electronic components are required to ensure efficient and safe operation of battery systems, especially in electric vehicles (EVs) or renewable energy storage systems. These components are, for example, a battery management system (BMS), a cell balancing circuitry and various sensors for current, temperature and battery voltage that provide real-time data for monitoring and control purposes (shown schematically in **Error! Reference source not found.**). With modules/battery packs, small manufacturing deviations between the batteries must be taken into account. It is therefore important to measure battery voltage at each individual battery so that the cell balancing circuitry can maintain voltages at similar values either by passive or active balancing. Temperature sensors tend to be placed sporadically in the battery pack to reduce packaging constraints, complexity and associated costs. Current measurement is usually carried out at pack level, while in certain applications current measurement at module level is also possible in order to monitor and optimise battery performance more precisely.

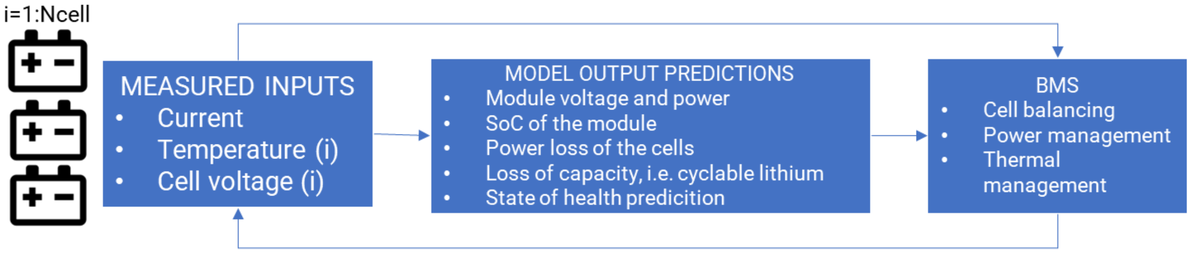


Figure 5 Conceptual figure of inputs and outputs of the electrochemical model of a module/battery pack interacting with sensors and BMS.

At the cell level, a battery model corresponds to a battery. On the other hand, at the module/pack level, it is not feasible to use Ncell battery models for each battery due to the high computational complexity. This applies in particular to physics-based models such as the P2D electrochemical model, but also to the current state-of-the-art BMS battery models, where the execution of the models in real time is crucial. Instead of modelling each battery cell individually, the battery model uses a lumped set of parameters to represent the behaviour of an entire module/battery pack. The model's output predictions are the same as those of a single cell, with the only difference being that the outputs in terms of voltage, power and power loss are rescaled to the module/battery pack level. Non-dimensional quantities such as SoC, percentage loss of cyclable lithium and SoH remain in the same range as in the case of a single battery. The SoH of each individual battery within the module/battery pack could potentially be predicted by combining data from the model's lumped SoH prediction and the measured voltage response of an individual battery.

The BMS collects all the information from the sensors and the battery model output predictions and sends control signals to the cell balancing circuitry to balance the cell voltages or SoCs, to the power management to regulate the charging and discharging currents and voltage limits to ensure safe operation of the battery module/battery pack, and to the thermal management to activate cooling fans, heat pumps, etc. to maintain the optimum temperature of the batteries in the module/battery pack. In the event of abnormal conditions in the battery pack, such as deviations in the battery voltage, exceeding the minimum or maximum allowed voltages, exceeding the maximum allowed current and temperature value, the BMS can trigger shutdown procedures to prevent further damage or dangerous hazards, e.g. thermal runaway.

5. MdT and DT

Within the framework of battery testing advancements, the relationship between the Multidomain Toolchain developed on WP4 and the Digital Twin, developed in WP5 constitutes a significant aspect within the FASTEST project. This chapter delineates how the MdT integrates with the DT to facilitate and enhance battery testing virtual representations. The diagram depicted in **Error! Reference source not found.** is a representation of the systematic interaction between these entities.

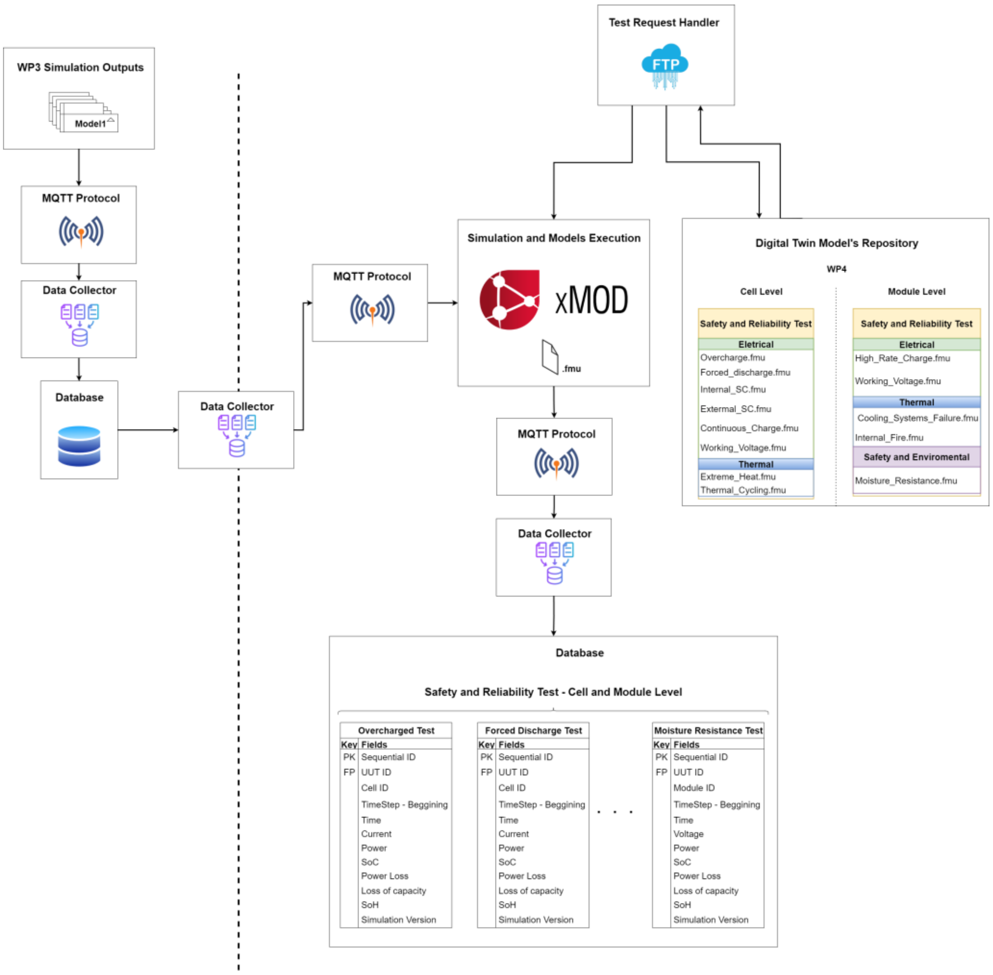


Figure 6 WP4 and Digital Twin integration.

The provided schematic encapsulates the MdT's integration with the DT, within the xMOD platform being a central component for simulation execution. The setup is designed to enable the application of WP3 simulation outputs as direct inputs for WP4. As the simulations from WP3 end, the resulting data sets form a foundational layer for the subsequent WP4 tests, fostering a data-driven approach to battery model validation and analysis.

In this configuration, the Test Request Handler is responsible for the initialization of the execution of the tests. It collects **FMU-standardized models** from the DT repository—a centralized hub for all simulations—and conveys them to the xMOD platform through **FTPS** communication.

It is important to note that the depiction of multiple MQTT protocols and Data Collector blocks within the scheme, while singular in practice, is intended to clarify their involvement in data transmission and collection. A singular MQTT protocol instance establishes a communication channel that is both robust and responsive, handling the influx of real-time data from the simulations. The Data Collector, on the other hand systematically gathers output data from xMOD simulations and populating the database, which serves as a structured repository for all test results.

Moreover, the Data Collector is not limited to a unidirectional role; it is equally adept at retrieving WP3 data from the database to serve as inputs for WP4 simulations over time. This versatile functionality underscores the seamless synergy between WP3 and WP4 ensuring that the simulations within WP4 are consistently informed by historical data, thereby maintaining the relevance and accuracy of the DT's predictive capabilities.

In the database design, each table corresponds to a distinct category of tests, incorporating several key fields for comprehensive tracking and identification. These include the Cell ID or Module ID and the specific Unit Under Test (UUT) to which they are associated. Additionally, the database captures critical data such as the start times of the simulations, their respective outputs, and the version of the simulation software used. This latter aspect is particularly crucial for monitoring any modifications or updates to the simulations over time. It's important to emphasize that the FASTEST project is subject to continuous evolution, implying that the database architecture and its components may undergo future adjustments to align with the project's evolving needs and objectives.

6. MdT internal specification

The Multi-domain Toolchain (MdT) is not just a modeling tool but a comprehensive framework designed to bridge the gap between theoretical research and practical application in battery system development. This toolchain aims to encapsulate a wide spectrum of analyses, from detailed electrochemical processes at the cell level to the complex interactions within battery modules and packs at the system level. Utilizing Matlab or equivalent high-level computational environments, the MdT will employ advanced algorithms and sophisticated simulation techniques. These methodologies are crafted to represent the intricate electrochemical and physical behaviors of battery systems with high fidelity. By fostering a modular approach, the MdT aspires to not only accommodate various sub-models for different aspects of battery behavior but also ensures scalability. This adaptability ranges from simulating single cells to entire battery packs, thereby providing a versatile toolset for analyzing and optimizing battery systems across different scales and complexities.

In developing the MdT, a structured approach will be paramount, potentially harnessing Matlab for its comprehensive simulation capabilities and its vast array of libraries and toolboxes. The development trajectory will be inherently iterative, commencing with foundational frameworks and gradually integrating more complex features and behaviors. Significantly, the outputs from Work Package 3 (WP3), which encompass detailed simulations of battery behavior and aging processes, will be integrated as critical inputs into the MdT. This integration ensures a seamless and accurate depiction of battery dynamics across various states of health and operational conditions. Collaborative efforts with domain experts and key stakeholders will play a crucial role in refining model parameters, aligning simulation outputs with empirical data, and iteratively enhancing the model's predictive capabilities. Documentation throughout the development process will be meticulous, ensuring that every phase of the MdT's evolution is transparent and well-documented, thus facilitating future enhancements and modifications.

Transitioning to the final development phase, the MdT will see the integration of cell-level and system-level models into a cohesive and comprehensive toolchain. This integration is critical, especially with the incorporation of data and findings from WP3, enabling a fluid transition from isolated cell simulations to a holistic system analysis. The unified toolchain will then undergo extensive validation processes to ensure its accuracy, reliability, and robustness under various operational conditions. Validation activities will include empirical data comparisons, sensitivity analyses, and scenario testing to encompass a wide array of operational conditions and potential fault cases. This exhaustive validation ensures that the MdT stands as a reliable, accurate, and versatile tool in the battery system development arena, capable of addressing the multifaceted challenges of battery design and optimization.

6.1 Cell level

At the cell level, the Multi-domain Toolchain (MdT) will concentrate on leveraging the outputs from Work Package 3 (WP3) to develop sophisticated algorithms aimed at enhancing our understanding of State of Charge (SoC) and State of Health (SoH) under various test conditions, including overcharge and internal short circuit scenarios. These outputs, embodying detailed simulations of battery behavior and aging, will be instrumental in constructing predictive models that can foresee the outcomes of such safety and reliability tests.

Employing pseudo-two-dimensional (P2D) models output or equivalent circuit models (ECM) output, coming from WP3, the MdT will simulate the intricate internal processes of a battery cell, focusing specifically on the critical safety aspects. These models will serve as a foundation for analyzing how different stress conditions, such as overcharging or experiencing an internal short circuit, affect the battery's performance, SoC, and SoH. The intent is to use these detailed simulations to anticipate the battery's behavior and responses during such adverse events, thus enhancing the predictive accuracy for safety assessments.

By integrating the data and insights gleaned from WP3, the MdT will refine these models to not only simulate standard operational parameters but also to test the battery's limits under extreme conditions. This approach will yield a comprehensive analytical framework that provides detailed insights into the cell's behavior, enabling the development of algorithms that can predict capacity fade, risk of failure, and overall life expectancy under various stress scenarios.

This comprehensive modeling strategy at the cell level is vital for developing a robust predictive tool that can effectively forecast the outcomes of safety and reliability tests, thereby guiding the optimization of battery design and operational strategies to ensure enhanced performance, longevity, and safety.

6.2 System level

At the module level, the Multi-domain Toolchain (MdT) will leverage outcomes from both cell-level analyses and safety assessments to enhance the simulation and understanding of battery modules. This approach will integrate the detailed electrochemical and physical behaviors of individual cells with the insights gained from safety and reliability tests, thereby providing a comprehensive and nuanced view of module performance under various conditions.

The MdT will use the cell-level data to model the interactions within the battery module, taking into account the collective behavior and potential safety risks identified during safety evaluations. This integration is key to understanding how individual cell characteristics and safety responses influence the overall system performance, especially during critical conditions such as overcharge or internal short circuits.

By combining the detailed insights from cell-level modeling with the robust safety analysis, the MdT at the module level will be able to simulate the electrical, thermal, and mechanical dynamics more accurately. It will also assess the impact of cell-to-cell variations on the module's performance, thermal management, and state of charge balancing, ensuring that the battery management system (BMS) can effectively maintain operational safety and efficiency.

This holistic approach at the module level will allow the MdT to predict potential issues and optimize the design and operational strategies of the battery module. It will enable the development of mitigation strategies to enhance the safety, reliability, and longevity of the battery systems, thus providing a critical tool for advancing battery technology in real-world applications.

7. MdT and life cycle

The objective of this section is to structure the development life cycle of the MdT into defined phases, regarding the safety and reliability of the system, following the requirements of the IEC 61508 standard.

Following the requirements and recommendations of the standard not only enhances the safety and reliability of the system, decreasing the risks of the development and enhancing overall system reliability, but also helps developing a software that is easy to maintain and update.

7.1 Life cycle requirements

During the development of the MdT, some general requirements shall be met to fulfil with the safety lifecycle:

Modular approach: The activities of the MdT development should be divided into elementary activities where the scope, the inputs, and the outputs of each of those activities are specified.

- Structured methodologies: The main aim of structured methods is to promote the quality of software development by focusing attention on the early parts of the lifecycle. The methods aim to achieve this through both precise and intuitive procedures to determine and document requirements and implementation features in a logical order and a structured manner. In the specific case of FASTEST, the MdT is divided into some of the different Work Packages and Tasks that comprise the project.

- V-model: A V-like lifecycle shall be followed to assure that the safety integrity is maintained during the different phases of the development of the MdT. Subsection 7.2 analyses the use of the V-model and the objectives and requirements of each of its phases.

- Use of appropriate techniques: For each of the phases of the MdT development, appropriate techniques shall be used to help fulfil the requirements of the phase. These techniques will be mentioned in Subsection 7.2 when each of the phases are analysed.

7.2 Phases of the life cycle

One important aspect for ensuring the safety lifecycle is that each of the development phases shall be divided into elementary activities, of which their scope, inputs and outputs shall be specified for each phase.

The lifecycle shall follow a V-model, as the one shown in Figure X, where each phase generates the necessary outputs for the next phase. The left side of the V-model consists of the development phases, and the right side consists of the verification and validation phases.

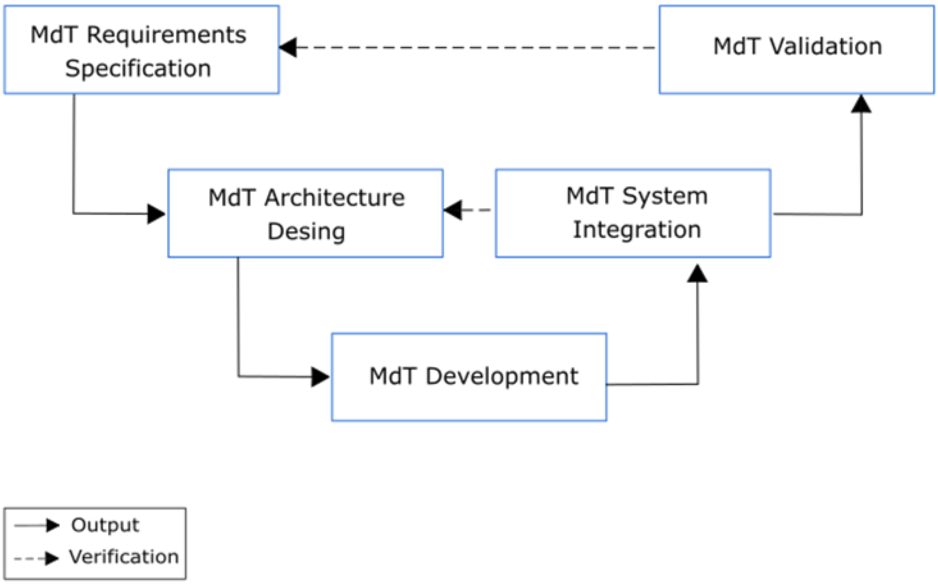


Figure 7 Life Cycle phases of the MdT architecture development

If at any phase of the lifecycle, the need of changes is detected in any of the earlier phases, an impact analysis shall be performed to analyze which modules are impacted, and the lifecycle should return to their respective phase on the left side of the V-model, repeating the necessary verifications for the impacted modules.

7.2.1 MdT requirements specification

The main objective of this phase is to specify the requirements that the MdT shall fulfil. The specification of the MdT requirements was carried out during WP1 and WP2.

From the safety and reliability perspective, it is crucial that the requirements are stated in a clear and comprehensible way, to minimize the hazard of errors that could compromise the integrity of the software and the overall safety and reliability of the MdT, as these requirements are what will be used as a baseline for the MdT architecture design.

7.2.2 MdT architecture design

This phase consists of the design of the MdT architecture, based on the requirements that were specified in the previous phase. The most crucial part of this phase is to ensure that the architecture design comes one with the requirements stated in the previous phase. The design shall specify the inputs, outputs, and parameters of the architecture.

From the safety and reliability perspective, it is important that the architecture design fulfils some safety requirements, to make the overall design more reliable and avoid possible mistakes during the development phase. These requirements include the following:

- Following a modular design, using abstraction and encapsulation to control the complexity of the design.
- Clear definition of the information flow between different elements of the design.
- Clear definition of the sequencing information and the timing constraints.
- Clear definition of fault and exception handling.

This phase is developed during task 4.1 and its output is this document, D4.1.

As for the nature of the FASTEST project, some of the requirements may have to change as the design advances. In that case, the impact of those changes shall be studied, and the design shall be revised, to reassure that it still fulfils the requirements.

In the same way, during the development phase the design may be required to change. If that happened, the safety and reliability requirements shall be considered, studying the impact of those changes in the ongoing development.

7.2.3 MdT development

The main aim of this phase is to develop the MdT based on the architecture design carried out during the previous phase and stated here, in D4.1.

With the aim of maintaining the system safe and reliable, the recommendations of the IEC 61508 standard shall be followed. Following these recommendations helps avoid introducing systematic errors and faults, thereby making the system more reliable and consistent.

During this phase, these requirements shall be considered and fulfilled:

- Following a modular approach: Help control complexity of the system and facilitate software modifications in the future. For achieving this requirement, software module size shall be limited, decomposing complexity into understandable units. Furthermore, the subroutines and functions that compose the modules shall have only one entry/one exit point and a fully defined interface.

- The different modules should be encapsulated. Globally accessible data can be accidentally or incorrectly modified from different modules of the code, and any changes to these data structures may require detailed examination of the code and extensive modifications. Therefore, key information should be ‘hidden’.

- Exception handling: The MdT shall implement exception handling mechanisms, to assure system stability when abnormal scenarios occur, and to minimize the possible errors introduced during the development.

- Implemented code must be readable, understandable, and easy to test. Following these rules makes the toolchain more maintainable and facilitates the modification and update of the code.

7.2.4 MdT system integration

The aim of this phase is to integrate the different modules developed during the different phases of the project, integrating the different models generated in the WP3 with the MdT developed in the previous phase of the lifecycle, in T4.2. It is also crucial to validate that the integration fulfils the design carried out on D4.1.

To assure the safety and reliability of the system, and to obtain a system that is consistent with the real scenario, it is important to follow some general rules and recommendations during the integration of the modules and the validation of the integrated system.

It is important to note that the modules developed during the WP3 shall be also thoroughly tested, but that testing is out of the scope of the MdT. Anyhow, the general recommendations for this phase could and should be applied for the testing of the individual modules during T3.4.

The requirements and recommendations that shall be followed during the validation of the integration are the following:

- The integration of the software shall be divided into manageable sets, helping the integration and the testing of each of the individual tests.
- Clear definition of the test cases and the data needed for each test case.
- Clear definition of the test criteria on which the result of each test case will be judged.
- The test specifications shall state the procedures required for corrective action on failure of test.
- The results of the integration tests shall be documented, stating the results, and whether the objectives of the have been met. If case of a failed test, the reason for the failure shall be documented.

Every modification need introduced to the MdT during the integration phase shall be documented, and the impact of the change shall be studied, evaluating the need of a re-design of the MdT, going back to the phase ‘MdT architecture design’.

7.2.5 MdT validation

The objective of this phase is to ensure that the MdT complies with the requirements specified in the first phase of the lifecycle, ‘MdT requirements specification’.

In this phase, the validation activities shall be carried out as specified in the requirements specification. The results of the activities shall be documented, following a chronological record, to permit the retracing of the sequence followed to validate the MdT.

When discrepancies occur between the expected results and the actual results, it shall be analysed whether to continue with the validation or to return to an earlier phase of the MdT lifecycle. The decisions taken shall be documented as part of the validation results.

The validation shall meet the following requirements:

- The main method for validating the MdT shall be testing.
- Testing scenarios shall include the following:
    1. Normal operation scenarios
    2. Anticipated occurrences: Scenarios that are expected to happen but may not occur during normal operation, such as faults that the software must detect.
    3. Undesired conditions requiring system action: Scenarios that are undesirable, and the MdT shall handle them to ensure the integrity and safety of the system.

When the validation is done and the results are as expected, the lifecycle will get to an end, with the MdT design successfully integrated and meeting all the requirements specified during the specification phase.

8. CONCLUSION

This deliverable defines the requirements for the multidomain tool change, which could be used as a baseline for the WP4 after the FASTEST project. In this regard, all the requirements in terms of the interfaces between the model that will be developing the word package 3 and the word package 4 have been discussed, as well as all those requirements that deal with the integration of the multidomain tool change with the digital twin of the project. This investigation has been done based on the cell and also the system level for several applications, including stationery, the automation industry, and off-road applications. The key aspects in terms of the list of these tests that will be considered for the safety assessment of the cell and the system level within the framework after the tool chain has been discussed, as well as all those requirements that need to be considered at this stage for the buildup of the model and the tool chain in the WP 4 in order to be handed over later on for the WP 5, have been discussed.

9. References

[1] J. Newman en W. Tiedemann, „Porous-electrode theory with battery applications,” *AIChE Journal,* vol. 21, p. 25–41, 1975.

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