Early validation of heterogeneous battery systems in the railway domain

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2022 IEEE International Systems Conference (SysCon) | 978-1-6654-3992-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/SysCon53536.2022.9773852

***Abstract*—In general, trains are referred to as environment-friendly transportation means when compared e.g. to cars, busses, or aircraft, being modern trains electrified systems. Unfortunately, the costs due to creation and maintenance of railway infrastructures, notably the overhead lines to power the trains, impose boundaries to their expansion potentials. In this respect, the advances in battery technologies are disclosing new opportunities, like serving partially electrified tracks. In particular, on board batteries can be used as backup energy where overhead lines are not available. In such scenarios, analysing battery requirements and evaluating possible solutions is of critical importance.**

This paper proposes a model-based systems engineering methodology for evaluating the feasibility of heterogeneous battery systems in the railway domain. The methodology leverages separation of concerns to reduce the complexity of the problem and abstracts the different railway system components by means of corresponding simulation models. The methodology is illustrated through a study performed at an industrial partner; in particular, the paper discusses how simulation models have been conceived, refined, validated, and integrated to analyse the properties of various battery configurations for several passenger trains operating on commercial lines in France. Interestingly, the results demonstrate that heterogeneous battery systems provide a suitable trade-off alternative when compared to homogeneous batteries.

***Index Terms*—Model-Based System Engineering, Heterogeneous Battery Systems, Railway, Trade-off analysis, Simulation, Simulink**

I. Introduction

Railway is one of the oldest and most widespread transportation means, providing affordable travel options from short to long ranges. Modern trains are electrified systems, making railway transportation a suitable choice to reduce environmental impacts. A fundamental limitation to expansion in the railway domain is the cost, which is not only due to construction of the necessary infrastructures but also due to maintenance [1]. Overhead lines, technically called catenaries, are the standard means of supplying trains with propulsion power, and require a robust infrastructure along the tracks. In this respect, railway industry must take care of those scenarios, especially common in remote areas, where continuous catenary connections do not always exist. Tracks with these infrastructure limitations typically rely on hybrid propulsion systems: traditionally, electric and diesel engines are combined and the latter ones are activated wherever catenaries are not available. More recently, as electrification spreads and battery technology improves, diesel engines are being replaced by introducing battery-driven trains.

Battery-driven trains disclose a number of important benefits; from a technological perspective, as most trains are already electric the interfaces are easy to integrate. From operational points-of-view, battery (re-)charges can be performed when catenaries are available, so even while the train is running. Additionally, battery systems can benefit from regenerative braking, as large amounts of energy are recuperated and can be used for charging when trains need to decelerate. These extend operation possibilities if compared to for example diesel or hydrogen solutions, that need refuelling in stationary conditions. Moreover, batteries can provide emergency services in case of line-failures [2].

Lithium-ion (Li-ion) can be considered the standard technology for battery systems for electrical vehicles (EVs) in general and trains in particular. In large part this is due to the rechargeable nature coupled with relevant capabilities in regard to power output and energy density [3]. Nonetheless, Li-ion batteries research is very active and investigating alternative designs and different material combinations to achieve specific cell properties [4]. Indeed, the US Federal Railroad Administration has investigated the properties of various cell chemistries for the railway domain, and assessed that there is no clear best option for the general case, rather a case by case approach is necessary [5]. Therefore, the concept of combining different types of cell chemistries in the same system, that is heterogeneous battery systems, is attractive as potentially providing a broader solution space and more sophisticated designs.

This paper proposes a methodology for exploring trade-offs in heterogeneous battery systems for the railway domain. As the system is large scale and rather complex, a model-based system engineering (MBSE) approach is proposed [6]. In particular, the approach relies on a variety of models representing a railway system at higher-levels of abstraction and from different perspectives, thus conveying separation-of-concerns

This work is partially funded by the European ECSEL/Horizon 2020 AIDOaRt project and the Swedish Knowledge Foundation SACSys project.

[7]. In this way, the development can be partitioned into smaller, less complex sub-problems to be handled; moreover, it makes it possible to explore by simulation a large set of possible alternatives, an option that would be impracticable by testing real systems due to (at least) time and costs.

The design and development of the proposed evaluation approach for heterogeneous battery systems has been carried out in collaboration with an industrial partner in the railway domain. Thanks to the collaboration, heterogeneous battery configurations could be first tested on a small-scale physical circuit and then validated against industrial battery models. Moreover, multiple simulations have been run to explore trade-offs in various configurations of heterogeneous battery systems and taking into account different trains.

The paper is structured as follows: next Section provides the reader with the basic concepts that underpin the rest of the contribution, while Section III discusses research efforts related to this work. Section IV illustrates the process followed for the design and development of the MBSE approach for evaluating heterogeneous battery systems in the railway domain. Section V and VI describe how the approach has been practically realised and validated against measurements collected from real battery systems, respectively. Section VII draws conclusions and discusses possible future investigation directions.

II. Background

Transportation systems design and development has been facing increasing complexity, especially with the extended use of software. Modern aircraft, cars, or space shuttles, represent among the most sophisticated systems human kind has been able to produce. As a consequence, design and development methodologies have evolved to cope with the increasing complexity; notably, MBSE is widely recognised as an appropriate methodology to alleviate the complexity of modern systems [6], [8]. Nonetheless, in industrial domains as railway that make use of large battery systems, often the design estimations have to be compensated via large margins or over-engineering, giving place to inefficient solutions. Indeed, the design of battery applications is a complex matter due to non-linear behaviours and lifetime impacts: battery dynamics are tightly coupled with the relative demands during charge and discharge [9]; in many domains batteries' life cycle estimations are critical due to the effects of ageing and wear [10]. As additional concerns, safety issues and the general care of batteries have to be considered due to the risk of critical chemical reactions, such as thermal runaway [11]. As a matter of fact, thermal runaway is often considered the primary safety risk for EVs [12].

A Li-ion battery can consist of various materials to create different chemical compositions, notably Lithium titanate (LTO), Lithium-nickel-manganese-cobalt (NMC), Lithium-nickel-cobalt-aluminium (NCA), etc; correspondingly, the resulting battery performs with varying characteristics. Since these characteristics can fluctuate significantly between cell chemistry manipulations, battery research often seeks for compromises with respect to the most critical factors. Typical examples of relevant factors to be traded-off are capacity versus ageing, output power versus energy density, and so forth [13]. As battery technology matures, new means of creating battery chemistries are engineered [4]; at the same time, advanced battery management systems (BMSs) can optimise run-time efficiency and improve safety capabilities by increasing performance and cell discharge cycles while maintaining safe operation [14]. Furthermore, there exist solutions devoted to the dynamic configuration of cells and adaptive batteries able to tune the internal connections to achieve desired electrical properties [15].

Given the variable characteristics of different batteries, it is in general desirable to perform a wide range of tests to understand and verify their behaviour when used on a certain system. However, this is often difficult in practice due to the complexity of battery systems as mentioned so far; moreover, it is worth noting that analysing lifetime impacts for variants of cell chemistries would imply measuring battery performances placed on systems with 10+ years of expected life span [10]. As a consequence, simulation is widely used as a verification and validation approach for battery systems.

The behaviour of a battery integrated in a system can be simulated by adopting models that are reliable representations of battery features and that abstract away all those details not relevant for the analysis of a certain cell chemistry. In the EVs domain, two main modelling approaches are used to create battery models: electrochemical and equivalent electric circuit, or equivalent circuit [16].

Electrochemical models [17] are detailed representations of batteries' chemical reactions and include the interactions with the environment. They enable very accurate simulations with respect to the different chemical and physical phenomena regarding a battery [16]. However, these models tend to be rather extensive and demand fine-grained details about the chemical composition of battery cells as well as the environmental conditions in which the battery will operate. In turn, also the complexity of simulation environments tends to grow remarkably. Therefore, electrochemical models are typically used in late design process stages, notably to analyse cell heating characteristics of a particular chemistry [18]. Alternatively, they can be used to provide control values for the validation of other battery models used for the simulation of the integrated system [19].

The equivalent electrical circuit model abstracts the battery properties to electrical components. In other words, a battery is modelled as an appropriate system of a voltage source, resistors, and capacitors [20]. The great advantage of this approach is the simplification of the model creation for a certain battery, which often also eases the integration with other parts of a larger system. However, due to the abstraction choice simulation results cannot achieve the same level of granularity of electrochemical models, especially for larger battery packs. In the railway domain, and more in general for EVs, the equivalent circuit model is extensively used for simulation [21]. The main reasons are that it allows for integration simulations with other system parts while keeping a rather simple model for the batteries (when, as for this work, electrochemical details are not relevant at such early development stages). Moreover, when needed the modelling approach can be extended and scaled by means of additional electrical components.

This paper proposes a simulation approach for validating heterogeneous battery systems in the railway domain. In this respect, the solution adopts the equivalent electrical circuit model approach with an extensive test suite. In particular, by altering several battery parameters, the goal is to evaluate different types of heterogeneous batteries and levels of state-of-health (SoH). In this scenario, SoH is related to the internal impedance and capacity of cells, which increases and decreases during operation, respectively. Therefore, by simulating the system with various levels of SoH it is possible to evaluate the viability of a system at various ageing levels. In turn, this can be used to compute estimates of expected discharge cycles until a battery system is unfit for use, which is an essential metric for evaluating feasibility in the railway domain.

III. Related work

MBSE is established in the automotive industry [22]; in particular, MBSE of EVs is an active reseach area [23]. Doufene et al. [24] discuss system design for EVs with a particular focus on choosing suitable architectures with respect to use cases revolving on power management (drive modes, charge and discharge cycles). A similar MBSE approach is presented in [25] where a domain specific language is used to design Li-ion battery powered EVs; the goal is to automatically determine viable solutions with respect to sizing a battery for the system under study. Moreover, Rodt et al. [26] illustrate a system engineering approach for designing a heavy-rail network infrastructure, including requirements, architecture, interfaces, and side operations related to parts of the infrastructure. In particular, the approach enables traceability between requirements and parts of the system as well as change-impact analysis. These works handle systems engineering through static analysis of the desired properties, which can be very useful to anticipate feasibility problems early in the development process and also to evaluate the consequences due to maintenance and evolution modifications. However, when uncertainties related to the properties of the system cannot be resolved through static analysis, dynamic models of the system are required, notably to simulate its behaviour. In this way it possible to evaluate better run-time capabilities of the system: for instance, in this work we use simulations to have a more precise estimation of heterogeneous battery performances when used on trains riding a specific track, described in more detail in section IV.

Simulink models are used in the context of MBSE for simulations in the railway domain; more specifically, in [27] the authors discuss the simulation of trains braking behaviour to compute distance boundaries for safety reasons. More

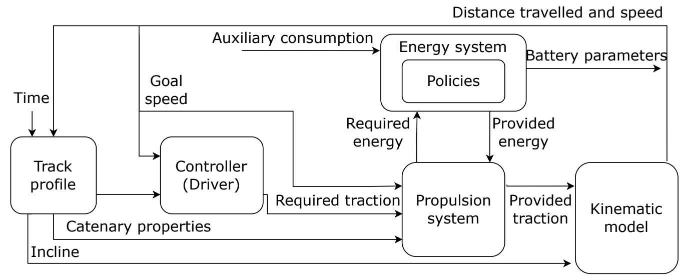

Fig. 1. Overarching description of the system architecture and model dependencies.

closely related to this work, Akhoundzadeh et al. [28] propose a simulation approach to evaluate power management solutions for hybrid trains, that is powered by hydrogen fuel and Li-ion cells. The authors adopt a similar MBSE methodology to the one proposed here, in which simulation models are introduced for the power sources, the power split, the controller, and the vehicle dynamics; based on these models, simulations are run to inspect system behaviours. Differently from this work, the paper in [28] mainly targets trains performance evaluations keeping the combination of hydrogen and Li-ion cells as fixed. On the contrary, this work aims at evaluating the performances of varieties of heterogeneous Li-ion cells and their integration in railway systems.

Also when considering simulation in the context of MBSE for EVs, many of the proposed approaches are based on Simulink [29]–[31]. In particular, Marco et al. [29] back up a MBSE solution for hybrid EVs with simulations aiming to evaluate power consumption in different system configurations; similarly in [30], [31] the authors create detailed simulation models of EVs to determine their power demands and correspondingly determine battery sizes and vehicle performances (e.g. the range with a full charge). Again, in general these simulations investigate EVs performances by considering fixed properties for the batteries and extensions to the simulation models would be needed to enable the simulation for heterogeneous solutions proposed in this work.

Typically, model validations are required whenever battery properties need to be simulated with a certain degree of confidence. In these situations, a common solution for simulation of an EV and the related battery models is through Simulink/MATLAB and an equivalent circuit model [16], and this work consistently uses the same approach. Nonetheless, there exist alternatives providing more fine-grained models like mathematical models [19]. These models can generate more detailed results from simulations, e.g. thermal behaviours of batteries. However, they tend to be more difficult to integrate with the other relevant perspectives of the system thus limiting simulation capabilities at the integration level [16].

IV. The proposed MBSE methodology

MBSE is widely accepted as an appropriate methodology to deal with the increasing complexity of modern systems [6]. This section illustrates a MBSE methodology developed for analysing the integration of heterogeneous batteries in railway systems. In particular, the proposed methodology leverages model-based simulation to explore different battery configuration alternatives when integrated in a train. Moreover, the methodology greatly benefits of separation-of-concerns, since the integration of batteries on a train needs to take into account several concerns, ranging from the propulsion system of the train to the track on which the train is expected to ride.

Conceptually, Figure 1 depicts the components involved in the integration analysis together with their interconnections:

- Track profile: represents the track characteristics on which a train rides, and includes train states and environment details. Notably, the inclination of the track is used to compute the kinematics of the train, each position owns a reference speed at which the train is supposed to run, and there is information about the availability of external power (catenaries);
- Controller: models a train driver. In particular, based on current and target speed it produces traction demands for the propulsion system;
- Propulsion system: describes the management of motors. It takes as inputs the current speed and the desired traction, and based on the availability of catenaries provides the necessary traction to the system through external power or by means of the batteries, respectively;
- Energy system: represents the characteristics of the selected battery system and its behaviour, together with its interactions with the rest of the train, like energy demands for traction, auxiliary energy consumption;
- Policies: is a sub-component of the energy system used to model the operational policies with which the batteries are managed, e.g. with respect to charge/discharge behaviours;
- Kinematic model: describes the kinematic behaviour of the train running on a certain track based on the position and traction provided by the propulsion system.

Already at this point it is worth noting how the separation-of-concerns principle allows to reduce the complexity of the system by tackling it as a set of smaller sub-problems. Moreover, the partitioning discloses the opportunity of adopting models at different levels of granularity, depending on their contribution to the simulation of the integrated system and the corresponding needs for precision.

The specification of the various models constituting the simulation architecture shown in Figure 1 followed an iterative process, where each model was developed depending on the simulation needs and validated against reference data available at the industrial partner. Figure 2 details the various steps traversed in the process in order to create the final models due to trade-off simulation and analysis.

By going into more details, starting from the conceptual simulation architecture presented in Figure 1, corresponding Simulink models were created (tag 2 in Figure 2); apart from the conceptual architecture (tag 1), these models have been conceived by referring to technical data available at the industrial partner. In particular, the kinematic model was based

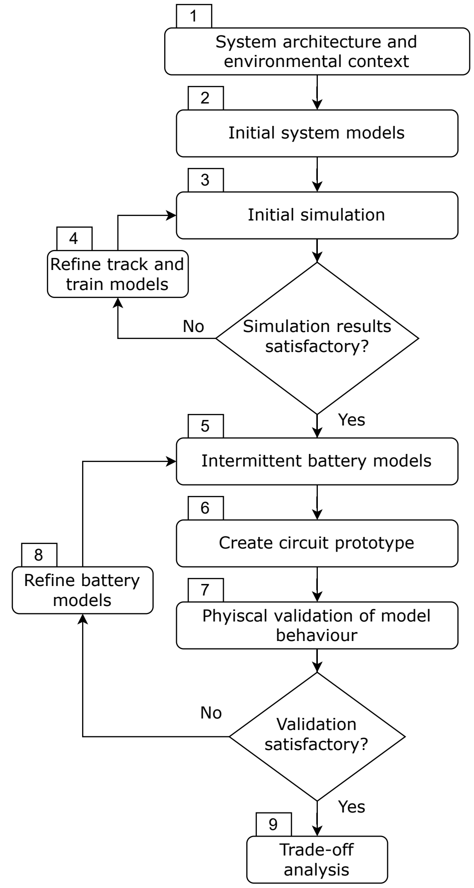

Fig. 2. Flowchart of the proposed MBSE methodology.

on a previous work that evaluated efficiency on the same type of trains taken into account by the simulations in this paper [32]. Moreover, a simple battery model was adopted by referring to existing data on commonly used battery systems, while various track profiles were adopted from commercial lines in France.

The initial models generated simulation results to be validated against three specific vehicles' data available at the industrial partner. Firstly, the feedback from the validation was used to refine simulation models for track and train properties until deemed satisfactory (tag 3 and 4). Subsequently, the results obtained from simulations allowed for an analysis concerning the operational demands and necessary electrical capabilities for the battery system. This was realised through equivalent electrical circuit models for the batteries (tag 5), and a corresponding (physical) electrical circuit (tag 6 in Figure 2). In fact, as the energy system could not be validated towards any previous data or tests, some internal validation was required especially targeting electrical capabilities as well as the feasibility of management policies (tag 7 and 8). Eventually, experiments on the physical circuit permitted the achievement of a satisfactory control system for the output of the battery system, which was replicated in the simulation models. In particular, the control system was based on high-

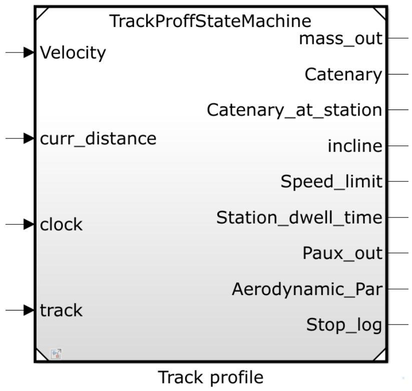

Fig. 3. An excerpt of the track profile Simulink model used for the simulations.

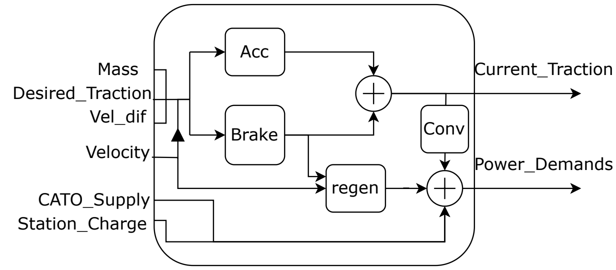

Fig. 4. An excerpt of the propulsion system represented in Simulink for simulation purposes.

frequency switching.

Eventually, the trade-off analysis followed a Design of Experiments (DoE) [33] approach (tag 9 in the Figure). In particular, the analysis has been aimed at determining the impacts related to batteries due to the following variables: battery configuration, that is number of cells per type; policies of battery management for each type of cells, like round-robin, random, power consumption thresholds; SoH for each type of cells, that is internal impedance and nominal capacity; other system characteristics, i.e. mass of the train, incline of track, auxiliary demands due to travel conditions (e.g. external temperature, dwell time). In order to present the results in an understandable way, analysis outcomes have been represented by adopting response surfaces [34]. By going into more details, a series of sensitivity analysis graphs have been used to show the relation between the State-of-Charge (SoC) and the variation of the other parameters taken into account. As expected, SoC is of particular interest as it is the primary measurement of the energy stored in the battery and can provide an understanding of the vehicle's remaining range, thus useful to evaluate the feasibility of battery configurations over different tracks. Furthermore, the depth of discharge (i.e. the % of discharge with respect to the fully charged battery) relates directly to ageing [35], which in turn is a critical parameter for estimating available discharge cycles of a particular solution.

V. Implementation details

The main implementation artefacts obtained through the methodology described in Section IV consisted of Simulink models to be used for simulations of the integrated system. The prominent implementation choices for the different models depicted in Figure 1 are discussed in this section together with excerpts of the corresponding Simulink models. The interested readers are referred to [36] for more details on the developed artefacts.

An excerpt of the track profile model is shown in Figure 3: it embedded a state machine for the train and parameters related to the position on the track. By going into more details, based on a clock and the position on the track (`curr_distance`), the train state would transition between standing at stations and travelling between them. Moreover, each position has been linked to additional data, like the incline of the track, the speed limit, the current mass of the train (passengers vary between stations), auxiliary power demands (`Paux_out`), the availability of catenaries both on the track and at stations, and the dwell time at each station. Eventually, the model has been made parametric with respect to different tracks and trains: the `track` input is used to select a specific track among the available profiles while the kind of train is set internally in the model and affects, apart from the mass, different aerodynamic parameters returned as `Aerodynamic_Par` by the simulation model.

The driver has been implemented using a simple proportional–integral–derivative (PID) controller. In particular, the PID has been tuned to model the "all-out" test behaviour, that is keeping the desired speed output for the propulsion system equal to the maximum speed allowed on the current track segment. In this way it has been simulated the most significant strain on the system, which is the crucial case from a viability analysis standpoint.

The propulsion system consisted of mathematical models of the drive chain and electrical motors already available at the industrial partner and validated for other internal simulations. An excerpt of the model is depicted in Figure 4: the inputs are the current velocity, the external power supply (`CATO_Supply` and `Station_Charge`), the current mass of the train, and the target velocity and traction. In the figure a high level description of the internal structure is given: the `Acc` and `Brake` blocks represent the motor and surrounding equipment for the propulsion system, while the `regen` block describes the generative braking. As outputs of the simulation, the propulsion system model generates traction forces and power demands that are used as inputs for the kinematics and battery models.

The kinematics model has been used to simulate the train riding on a specific track. As illustrated in the excerpt in Figure 5, it takes as inputs the traction applied by the propulsion system, the current mass of the train, the gradient of the track in the current position, and the aerodynamic parameters of the train (`Aerodynamic_Par`), and generates as outputs the updated velocity and position for the train. Internally, the

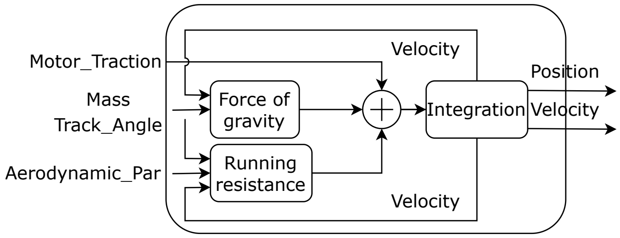

Fig. 5. An excerpt of the kinematics model used for the Simulink simulations.

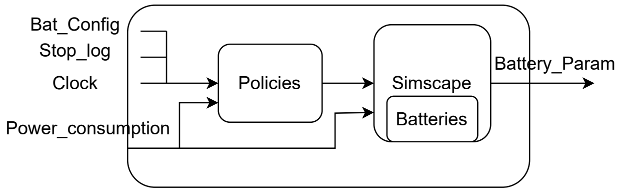

Fig. 6. An overview of the Simulink battery model used for simulations.

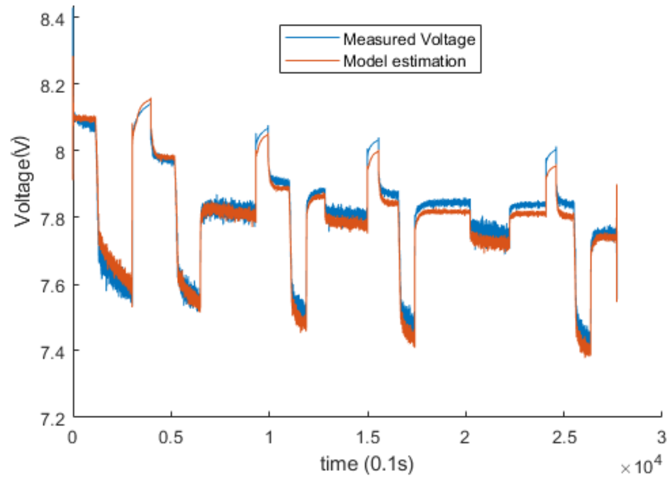

Fig. 7. Comparison of model and real measurements on the prototype circuit.

input parameters are used to determine the force of gravity and running resistance, which in turn are used for integration to compute the updated position and velocity for the train. These parameters are used in a feedback loop both internally and as inputs for the track profile and propulsion system to compute the next step for the simulation.

The energy system included a battery model and a power manager for the policies; an excerpt of the simulation model is shown in Figure 6. This model takes as inputs (apart from `Stop_log` used for utility purposes): the demands of power, both coming from air conditioning, lights, etc., and the propulsion effect that can be either a request of energy for propulsion or a contribute of charge thanks to generated energy via regenerative braking (`Power_consumption`); the battery configuration, that is partition of cells and governing logic for charge and discharge (`Bat_Config`). Internally, there exists a policy block that consists of various MATLAB scripts due to battery management (`Policies`), and a Simscape environment to model batteries behaviour from an electrical point of view, which acts as an interface to the rest of the Simulink model (more information can be found in [36]). The battery model generated simulated battery values for various combinations of tracks and trains, and the outputs have been collected in terms of SoC for the heterogeneous system as well as for corresponding homogeneous systems for comparison, i.e. made of only NMC or LTO.

By going into more technical details, the initial simulation models for the energy system have been conceived using the method proposed in [37], that is an equivalent circuit model has been created by relying on the sole data sheet values for the batteries. After the initial simulation phases, the characteristics of battery power demands could be better analysed in collaboration with the industry partner, which also determined potential cells configurations and management policies. At this point, the simulation models needed a validation phase against a physical circuit to check that the results could be considered realistic with respect to cells behaviour (e.g. that the discharge or the switch between different batteries worked as modelled in the heterogeneous solution). Figure 7 displays the outcomes of a discharge event: in particular, the estimated values coming from simulations without any model tuning are compared with the measures using the prototype circuit. Here, it is worth noticing that by using the sole data sheet values to build the equivalent circuit model for the batteries it has been possible to obtain a relatively accurate simulation of the battery system. Indeed, the final battery model needed only minor tuning of the parameters.

VI. Results and Discussion

As mentioned in Section IV, once all the models were considered ready a number of simulations have been run to analyse the performances of heterogeneous battery systems under different integration scenarios. In particular, three different trains and multiple tracks have been simulated together variable management policies for the batteries and their SoH. As the results were obtained at a similar level to abstraction as the one of the simulations used for internal design evaluations at the industry partner, the comparison to previous results proved straightforward to interpret.

The results of the trade-off analysis provided interesting feedback about heterogeneous battery configurations and potential benefits. In particular, the feasibility of a heterogeneous system for different kinds of trains and tracks has been proved. Moreover, possible areas of improvement have been elicited regarding trade-offs between critical parameters like ageing, cost, and capacity. By going into more details, the evaluation indicated that a nominal heterogeneous battery with an even split of cell types generates a solution representing a middle-ground between the characteristics of the combined cells. Furthermore, different management policies could be used to tune and diversify the impact of the potential trade-offs, mainly affecting attributes such as ageing.

Figure 8 illustrates the trade-offs resulting from the use of a heterogeneous system with an even split of cells and without any particular operational policy or optimisation. Overall, the

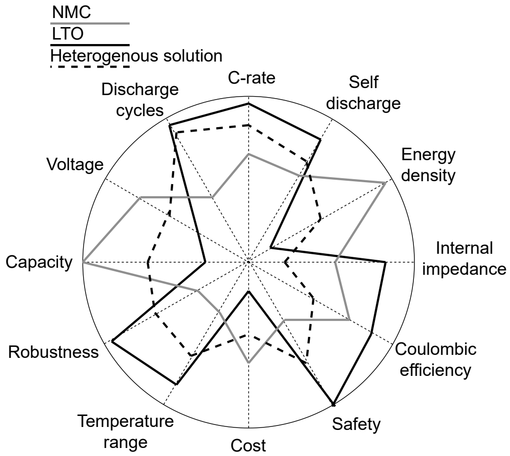

Fig. 8. A spider diagram illustrating comparative results of a nominal heterogeneous solution against homogeneous solutions made of NMC and LTO cell types.

heterogeneous configuration performances tend to stay in the middle between the best and the worst alternatives. The C-rate for the heterogeneous battery is a middle value between the homogeneous LTO and NMC cell types; indeed, the discharge rates are directly coupled to the cell chemistry, so an even combination of cells is expected to result in the mean value. Similarly, self discharge, energy density, capacity, and voltage are in the middle with respect to homogeneous configurations. When considering the internal impedance, the heterogeneous solutions perform worse than homogeneous one because the batteries can be constructed with less parallel connections (different types of cells cannot be put in parallel combinations). The same results are obtained for the coulombic efficiency, which is primarily affected by the switching mechanisms.

A number of relevant parameters show the potentials of heterogeneous batteries when switching opportunely between different cells: the discharge cycles parameter is one of the most relevant ones, since adequate management policies could increase it by controlling and delegating the operational loads depending on the cells different strong points. Safety is another interesting area for improvements: the heterogeneous solution performs better than the less chemically stable cell types; additionally, smart architectures and operational control could further increase the performances by appropriately deactivating less chemically stable cells when needed. The temperature range of the cells depends on the cell chemistry, and with the heterogeneous solution it could be possible to create policies to keep low the heating for one cell type while increasing the same value for another type. The robustness of the system similarly finds a good compromise when more stressful behaviour can be delegated to the more robust cell type. Regarding cost, the different cell types contribute with their own different costs to a heterogeneous system. Nonetheless, the heterogeneous solution shows long term benefits with respect to the discharge cycles, which in turn could reduce battery costs.

The MBSE methodology and simulation models presented in this paper enabled the industry partner to evaluate innovative solutions without a heavy upfront investment. However, although the models used for the simulations were validated and verified they still generate approximate results. Notably, incline values for train tracks are given as averages for track segments, as in [38]; moreover, most variables have been considered constant values if the effect was small in the simulation context. The controller only evaluated simple driving patterns without optimisations. The propulsion system possibly relied on simplifications adopted by the industrial partner in their modelling process (even if internally verified and trusted in regards to the accuracy). The kinematic model has been kept significantly simple, although its accuracy has been verified in existing literature [32]. Eventually, the energy system was based on the equivalent circuit method, which abstracts many details into the electrical domain. This simplification does not allow, for example, to evaluate more fine-grained properties of batteries as heating. With respect to these approximation limitations, it is worth noting that the methodology proposed in this work gives the possibility to extend any simulation model in the system as per precision needs. Notably, since the level of details for a model is not bound to other models, the propulsion system was at much higher fidelity than the controller, without hindering the integration.

Extending the methodology and results presented in this work to other domains depends on how well the system components can be separated. In the railway domain, the interactions between the different models allowed for independent development and validation towards various levels of fidelity and detail. In other words, the applicability in other battery-driven application domains depends on how well the battery sub-problem can be isolated from the rest of the system. More precisely, for domains as railway the nominal case can be isolated from external disturbances and operational variations. In other domains like EVs, the nominal use case might cover a wide span of potential operational modes (e.g. city or highway) and be harder to model [39]. In such cases, a design of experiments approach might need to be extended to cover more aspects of the operation and hence more variability points.

VII. Conclusions

This paper presents a MBSE methodology to design and evaluate a heterogeneous battery system in the context of a battery-driven train. The methodology relies on model-based design and simulation of railway systems; the approach adopts the separation of concerns principle, and relies on a modular and extensible set of models to simulate real scenarios. The simulation models have been iteratively refined and validated in collaboration with an industrial partner. In particular, the simulation of the integrated system required models with varying fidelity degrees in order to perform trade-off analysis. These models consisted of: a track profile describing the physical properties of the track, a controller acting as train driver, the propulsion system, the energy system, policies for the energy system, and the kinematic models. Through simulation it has been possible to explore various system configurations and hence verify the potentials of heterogeneous battery solutions for battery driven trains. In this respect, the approach provided results relatively easy to understand and compare against the current system performances; moreover, the approach did not require any major upfront investment for the industrial partner. A major benefit observed with the heterogeneous system is the added flexibility in design, where different architectures and run-time policies create a more mature solution space for the application domain.

Future research efforts will be devoted to evaluate more precisely smarter battery management policies to cover other use cases. Moreover, the methodological principles proposed in this work are being extended for the automotive domain, and in particular for battery-driven racing cars.

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