Towards Adopting a Digital Twin Framework (ISO 23247) for Battery Systems

1st Johan Cederbladh
IDT Department
Mälardalen University
Västerås, Sweden
johan.cederbladh@mdu.se

2nd Enxhi Ferko
IDT Department
Mälardalen University
Västerås, Sweden
enxhi.ferko@mdu.se

3rd Emil Lundin
Development Engineer
Nordic Engineering Partner
Västerås, Sweden
emil.lundin@nepartner.com

***Abstract*—In this paper, we discuss how the emerging and novel technique of Digital Twins (DTs) can be applied in the battery domain to address current challenges. Notably, rechargeable batteries are central for modern applications of electric vehicles (EVs), consumer electronics, and wireless components. Several complex battery solutions are emerging in literature to support industrial needs. However, the increasing complexity of battery systems is negatively impacting measurements and control of batteries during run-time, critical aspects for efficient run-time management. DTs are seen as a promising solution, offering enhanced operational management and planning capabilities through real-time models that accurately represent the current states of batteries. This precision leads to enhanced accuracy in monitoring and decision-making processes. Despite the potential benefits, the lack of a standards-based DT framework for battery systems hinders industrial practitioners from adopting and implementing DT solutions. We discuss how DT solutions could elevate specific challenges in complex battery systems. Additionally, we discuss requirements for building DTs for the heterogeneous battery system use case and map them to the ISO 23247 DT framework. Eventually, we examine the suitability of the ISO 23247 DT framework for building DTs for complex battery systems.**

***Index Terms*—Battery systems, Digital twin, ISO 23247, Architecture, Requirements, Simulation, Real-time, Challenges, Heterogeneity, Interoperability**

I. INTRODUCTION

Increasing demands of sustainability and electrification are driving development for customer and regulatory satisfaction, and battery systems are on the rise in several domains, such as railway, automotive, aerospace, etc [1]. With the growing interest in battery technology advanced applications are continuously evolving to meet traditional challenges of performance, for example in the Electrical vehicle (EV) domain. More recently, technical advances have improved the run-time configuration of battery systems to be adaptable and applicable across a wider range of use cases [2], [3]. As a result, several paradigms have emerged, such as reconfigurable battery systems [4], software-defined batteries [5], and Heterogeneous Battery Systems (HBS) [6]. These solutions mainly improve the flexibility of battery systems to reduce over-engineering and improve the range of applicable use cases for a given system due to the run-time configuration that can cover a larger range of functional and non-functional requirements that need to be met simultaneously.

However, control of complex dynamic battery systems introduces new challenges and significantly increases complexity in the surrounding equipment. Notably, many key parameters of battery systems are not measurable directly, such as State-of-Charge (SoC), but instead estimated via indirect measurements at run-time [7], [8]. Additionally, without a clear view and subsequent control actions for the current state of a battery (particularly for complex systems) at run-time, there is a risk for increased ageing, faster capacity depletion, and safety risks [9]. As a result, estimation of essential parameters is required, and often simulation can be a valuable asset to predict with high accuracy and precision current (and future) states of the battery system [10]. However, combining simulation models with control logic for physical systems in real-time conditions is challenging. A novel solution to real-time usage of simulation entities in combination with a physical entity is the deployment of a digital twin (DT). A DT is a virtual representation that digitally replicates a physical component, system, or process, allowing for remote monitoring and control [11]. DTs are at this stage gaining some interest in the wider battery and EV community [12]. However, building such DT systems inherently exhibits complexity, and the absence of clear guidelines poses challenges for their adoption. Engineering DTs based on standardized reference architectures is an emerging necessity to streamline their development, processing, and integration [13].

In this paper, we identify and discuss the challenges for complex battery systems derived from our experience working with HBS [6], [14]. Subsequently, we put forth a set of requirements for building DTs designed to confront the unique challenges encountered in the HBS. We use the ISO 23247[1] digital twin framework. We present a mapping of the defined requirements in the ISO 23247 conceptual framework and demonstrate its applicability for the case of HBS. While ISO 23247 is a framework primarily designed for manufacturing processes, its versatile nature has allowed it to find successful applications across diverse domains. Notably, ISO 23247 has

---

This work was partly funded by the AIDOaRt project, an ECSELJoint Undertaking (JU) under grant agreement No. 101007350.

[1] ISO 23247 is available at: https://www.iso.org/standard/75066.html

been effectively employed in the construction industry to enable the safe and efficient operation of autonomous machines [15]. In addition, ISO 23247 is considered to be used in the agriculture domain [16]. Building on the success stories from domains beyond manufacturing and analysis of the HBS case, this paper advocates for the adoption of ISO 23247 for complex battery systems.

The rest of the paper is structured as follows; Section II details the necessary background and related work. Our research methodology is presented in Section III. We provide a motivation and context of the work in Section IV, and highlight our current solution in Section V. Finally, we discuss the paper in Section VI and conclude the paper while presenting future work in Section VII.

II. BACKGROUND AND RELATED WORK

Batteries, notably when consisting of Li-ion technology, are utilised extensively across various industrial domains. Li-ion technology provides a compact energy storage source with the possibility of recharging, often for thousands of charge-recharge cycles as performance degradation can be reduced via efficient management [17]. In its most basic form, a Li-ion battery consists of several battery *cells* which are configured in series and parallel connections to achieve the required electrical properties (e.g., capacity and voltage). The types of cell chemistries available on the market are many, and depending on the particular cell utilised parameters will vary, such as: Operational temperature range, discharge rate, ageing rate, energy density, and so on [18]. Several emerging concepts in the battery domain aim to improve the operational flexibility of (primarily Li-ion) battery systems. One proposed solution is the use of Software-defined battery systems [5], this enables an application to dynamically switch between energy sources during operation to prolong operational up-time. Another application area discussed in the literature is Reconfigurable battery systems [4], [19]. This type of system aims to enable the battery system to reconfigure the internal structure during run-time, via internal switching of the series and parallel connection of cells which improves efficiency. Another investigated use case is Dual battery systems [20], which is applied to wind power applications in electrical micro-grids. In this work, we mainly investigate HBS which is a complementary technique to those already mentioned [6], [14], and we discuss it further in Section IV.

A Battery Management System (BMS) is a necessity for modern batteries. In its most basic form, a BMS measures different parameters continuously in a battery and provides the user with information regarding the expected remaining capacity, possibly extended with different control mechanisms [21]. Common control functions of a BMS include safety mechanisms, for example, based on the current temperature to avoid thermal runaway events [22], or perhaps the power output [21]. More complex BMS functions include calculating state-of-health (SoH) which can also be estimated based on direct measures of a cell [9]. Indeed, measurements of batteries are typically limited to voltage (V), current (A), and temperature readings (T). This basic information is the basis for most BMS calculations, via extrapolation or experimental mathematical relationships [14], [17]. However, it is often challenging to effectively measure these parameters and accurately translate the measurements to the current state of the battery. Battery voltage, for example, will change dynamically during run-time depending on the load, and temperature needs to be measured on individual cell casings and then estimated for the internal temperature. Coupled with eventual degradation the acting equational relationships often need to be continuously re-evaluated to provide accurate estimations based on given measurement data. Typically, the direct measurements of a battery are fed into different models. In general, there are three main categories of battery modelling; Mathematical models, Electrochemical models and Electrical equivalent circuit network models [18], [23]. Mathematical models can include sets of differential equations describing physical phenomena for a battery, or stochastic models that include for example Markov chains. Electrochemical models are the most complex types of models, and in turn, considered the most accurate. These types of models are based on chemical and electrical reactions/phenomena, which require a rich level of detail and often many resources for accurate model simulation or execution due to the large sizes of models. The Equivalent Circuit (EC) models are the more commonly used type of model and are a middle-ground in terms of complexity and accuracy [24]. ECs are created by using common electrical components with well-studied behaviour in circuits. Recently, battery modelling has been integrated with the DT paradigm primarily due to the capabilities of prognosis and real-time control [25]. A DT can utilise any of the described models, and often several are used in conjunction for different purposes. A DT can be considered as a digital copy of a physical entity, where there is interaction between both in real-time conditions with the possibility for either entity to affect the other [26]. As such there are three main components, i) the physical entity ii) the virtual entity iii) the communication link between the two entities. We borrow the terminology from the ISO 23247 standard as it is one of the more mature standards for DTs available [13]. The use of DTs for battery systems is an emerging topic. Wang *et al.* [12] provide a research road-map for the use of DT technology to enable smart BMS. The paper identifies several potential benefits with the use of DTs as well as the key related technologies, with an emphasis on AI, the Internet of Things, and Cloud computing. Panwar *et al.* [25] discuss the advancements for BMS for Li-ion batteries of electric vehicles and note that DTs are a promising technology to tackle some of the problems with modern battery systems. Li *et al.* [27] propose a digital twin implementation of battery systems to enable BMS operation via the cloud. Qu *et al.* [28] introduce a method of utilising deep learning in combination with a DT to estimate the degradation of battery cells during operation. Although there are several identified related works, none of them propose a standard framework for DT, and we aim to bridge this gap with this work.

III. METHODOLOGY

The methodology employed in this study builds upon established case study research principles by Runeson et al. [29]. We identify some of the challenges for complex battery systems starting from the HBS use case and our recent research [6]. Then, we derive requirements for DTs of HBS. We thoroughly investigate the recently published ISO 23247 standard for digital twins and map the requirements to the reference framework proposed by the standard. This synthesis allows us to theoretically propose a standardised approach for developing DTs for HBS. To the best of our knowledge, this study represents the first adoption of the ISO 23247 framework within the complex battery domain.

IV. HBS USE CASE

This paper utilises the use case of a HBS [6]. At its core, a HBS is a system that utilises heterogeneous cells in a unified battery system, variance can exist in underlying chemistry, cell size, and cell wear. The heterogeneous sources are connected to a single output so that from an outside perspective, the system behaves and interfaces like any other battery system (i.e., a single input and a single output). The general context is visualised in Figure 1. The HBS takes as input external power that is converted via a `DC/DC converter` to supply a `Charge control unit`, which consists of a specific circuitry to divide incoming power to the different `Battery modules`. This division is based on current operational strategies and is controlled consequently via the `MCU` (micro-controller). The `HBS` includes n number of distinct `Battery modules`, where a module is a combination of one or more cells in parallel or series connection, and each module is *unique* but still connected on the same output to the `Load`[2] via a `Switching system`. The total current (both for charging the battery and for the external load) consists of the total sum of each module, and the `MCU` continuously tunes each module's proportion during run-time separately for the input and output. The `Switching system` implements the discharge strategy, which is maintained and supervised by the `MCU` based on inputs from an external `PC` containing various off-line analytics and simulation. Several sensors are active in the HBS during run-time, visualised in the figure with a sensor icon, and these are all connected to the `MCU` (possibly using different communication protocols).

The general architecture is similar for most battery systems used in modern applications, like EVs, however, complexity is added via the need for a switching control system. The switching capability is required so energy sources can be used for different contexts during operation, for example using one battery module for high-current discharge in a short time interval and another battery module for continuous low discharge. Previous investigations and prototyping have demonstrated improvements in metrics in ageing. However, the prototyping also demonstrated that the added complexity of the electrical switching requires advanced real-time control system interaction at run-time to realise positive results. Notably, high-frequency switching of battery cells induces increased dynamics in the typical battery measurements, worsening the already difficult measurement context of batteries [6], [14].

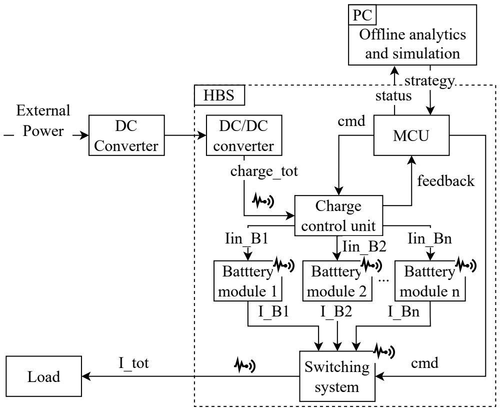

Fig. 1. Overview of a generic HBS

A. Challenges of HBSs

While the use of an HBS has been shown to alleviate some of the limitations of traditional battery systems, several open issues still exist to fully realise its potential value. These challenges (CH) are extracted from our use case and summarised as:

CH1. Estimation of key parameters during run-time: Due to the electrical implementation in an HBS (primarily the switching mechanism) the already difficult-to-measure parameters such as voltage and current become further complicated to measure directly, due to electrical switching. Instead, estimation is required based on continuous in-direct measurements during run-time.

CH2. Continuous refinement of control strategy: An essential part of an HBS is that it can use various strategies to allocate and adjust the active switching configuration. For instance, cells rated for high currents can be utilised during power spikes while cells with low internal resistance for prolonged discharge. However, the actual strategies need to be updated during the systems' lifetime due to degradation and run-time properties changing. An illustrative scenario is the adjustment of operational uptime for degraded cells to prevent excessive heating and mitigate potential safety risks.

CH3. Prediction of future degradation: Part of efficient battery management is to prolong the Remaining useful Life (RuL) of the system. Proper analytic and consequent adaption of operational strategy requires accurate and precise estimation of several run-time parameters such as cell voltage and cell-capacity, but also the accurate estimation of future states based on historical data in combination with momentous measurements to assist in operational planning.

---

[2] In the paper the load is arbitrary, but in a real application the load has a major impact on the operational strategies.

CH4. Maintaining a scalable and interoperable platform: HBSs are designed to incorporate various types of battery cells or energy sources. These sources may vary in chemistry, capacity, voltage, and other characteristics. As a result, one primary challenge is creating a system that can seamlessly adapt to different types of battery cells. In addition, HBSs may require frequent reconfiguration or expansion to accommodate changing energy demands or specific operational requirements. Ensuring that the HBS can easily scale up or down without significant hardware or software modifications is critical to the functional suitability of the system.

Addressing the above challenges effectively requires a combination of advanced technologies, data analytics, predictive modelling, and standardization efforts. In the following section, we present our strategy to tackle these challenges by designing DTs for HBSs that adhere to the ISO 23247 standard.

V. ADOPTING DIGITAL TWIN FOR HBS

In this section, we first reason the need for adopting DT for HBS by motivating its potential use to tackle each of the identified challenges. Thereafter, we define specific requirements to build a DT for HBS. Eventually, we discuss how the reference architecture proposed by the ISO 23247 standard supports the formulated requirements and its adaptation to the HBS use case.

A. Motivation of DTs for HBS

The presented challenges are a candidate for alleviation by the use of DT technology. Notably, real-time measurements with high-fidelity and high-accuracy simulations provides strong capabilities for HBS. Indeed, *Estimation of key parameters during run-time (CH1)* can be addressed by a DT due to the high-fidelity simulation models (perhaps several in parallel). For instance, DT could use continuous measurements from the sensors for voltage, current, and temperature to estimate the SoC and SoH for individual cells, ensuring precise control and optimisation. This also assists in *Continuous refinement of control strategy (CH2)* by including the high-fidelity models in a real-time control loop. The DT could use historical data in conjunction with real-time data to adjust control strategies to optimise parameters such as ageing, discharge rate, and safety. In a similar vein, *Prediction of future degradation (CH3)* can be achieved by a DT that leverages historical data in conjunction with real-time measurements to analyse specific cells and provide proactive maintenance and replacement. Finally, a DT alleviates *Maintaining a scalable and interoperable platform (CH4)* by utilising standardised communication protocols and data exchange formats.

B. Requirements of DTs for HBS

From our experience working with HBS in conjunction with the existing literature, we formulated a set of requirements for engineering DTs for HBS. Table I summarises the requirements and maps them to the identified challenges for HBS.

TABLE I
REQUIREMENTS FOR DTs OF HBSs MAPPED TO CHALLENGES

Requirement	Challenge
RQ1: Real-time data acquisition	**CH1**, **CH2**
RQ2: Data integration and fusion	All **CH**
RQ3: Realistic modelling of system's behaviour	**CH1**, **CH2**, **CH3**
RQ4: Simulation and testing	**CH3**, **CH4**
RQ5: Predictive modelling (algorithms)	**CH3**
RQ6: Adaptive control strategy	**CH2**
RQ7: Scalability and interoperability	**CH4**
RQ8: Data security and integrity	All **CH**
RQ9: User-friendly interface	All **CH**

In more detail, *Real-time data acquisition (RQ1)* is the most essential requirement given the dynamic nature of the HBSs. The system's behaviour can change rapidly based on external factors, operational conditions, and the state of individual cells. This requirement needs to be fulfilled to formulate real-time fine-grained control. The data gathered depends on the specific implementation, but should include common BMS metrics. *Data integration and fusion (RQ2)* complements *RQ1* as typically the data in an HBS is gathered from various sources (different sensors on each battery cell, switching system, charge control unit, etc.). Data integration allows a holistic view of the DT of the entire HBS and is essential for informed decision-making. Moreover, data needs to be fused to extrapolate meaningful information for control and monitoring under real-time conditions. Data fusion is also a base for creating *Realistic modelling of HBS behaviour (RQ3)*. With the gathered data, the eventual model needs to have high granularity in fidelity. For the HBS the structural parts of the battery are less interesting compared to the dynamics and a realistic model in this case captures the interactions between different components of the HBS. This includes how battery cells influence each other and how the overall system responds to changes in load, temperature, or other external factors. The realistic models are a foundation for *Simulation and testing (RQ4)*, which is mandated as a necessary capability to predict future states and to virtually test the system configuration(s). Moreover, simulation enables design space exploration of various operational scenarios, including extreme or rare events that may be challenging to replicate in a physical setting. This helps the DT anticipate and respond to a wide range of conditions. Similarly, *Predictive modelling (algorithms) (RQ5)* needs to be incorporated into the simulations to accurately predict degradation and maintenance. This approach minimises downtime and ensures that maintenance activities are conducted when most cost-effective and necessary. *Adaptive control strategy (RQ6)* allows DT to dynamically respond to real-time variations of diverse factors of the HBS to optimise the overall performance. *Scalability and interoperability (RQ7)* should facilitate the construction of a platform that can replace and augment the HBS setup easily (in both hardware and software), so that a common solution can be created for different use cases. The DT should also promote *Data security and integrity (RQ8)* so that the users are not at risk of data leakage or alteration during DT operation (mandated by most industrial cases). Finally, *User-friendly interface (RQ9)* is necessary to promote a wide audience in an industrial setting for utilisation of the technology, as the user base often is diverse and not DT experts.

A DT that fulfils all of these requirements should alleviate the challenges identified for the HBS case while providing beneficial capabilities for operation and management.

C. Conceptual framework of DTs for HBS based on ISO 23247

The ISO 23247 standard provides a framework for engineering DTs in the manufacturing domain. Specifically, Part 2 of the standard defines a reference architecture for DTs that includes an entity-based reference model [30]. Figure 2 illustrates how the entities and sub-entities of the reference models support the requirements for the HBS case.

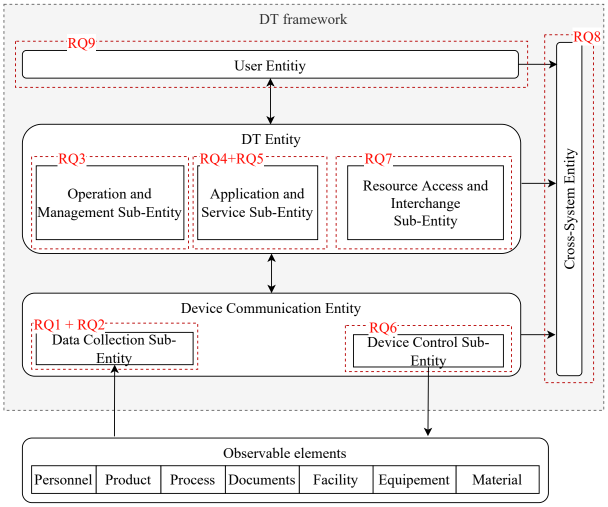

Fig. 2. Overview of the entity-based reference model of the ISO 23247 and its relation to the HBS DT requirements.

First, we note that the observable elements in our case do not cover the entire range defined in the standard, but should at least include the HBS (*Product*) and surrounding *Equipment*. The *Data Collection* sub-entity, as defined in the standard, covers the requirements related to real-time data acquisition as well as data integration and fusion. While the *Device Control* sub-entity would be responsible for sending commands to adjust the operational parameters of the HBS. The Data collection and Device Control Sub-Entities are separate in the framework, but they could also be implemented on the same MCU depending on the HBS implementation. As per the ISO standard, the DT Entity consists of the *Operation and Management* Sub-Entity, the *Application and Service* Sub-Entity, and the *Resource Access and Interchange* Sub-Entity. These Sub-Entities address various service-related requirements, including simulation, testing, and predictive modelling, and provide support for scalability and interoperability. The DT entity in the HBS case would be split into two parts, a real-time component which is placed directly in the HBS and an offline component which is placed in a more resource-heavy component (like a PC). In this way, a part of the DT would support real-time data gathering and feedback, while a second part would provide less time-critical inputs which could relate to the life-cycle of the system, such as ageing and control strategies. The *User Entity* provides an interface facilitating user interaction with DTs services, while *Cross-System Entity* is responsible for data security and integrity.

The ISO 23247 general framework matches the concrete needs of the DT HBS well, so although the standard is defined for another domain originally we find it to be a well-suited match. Indeed, each layer and component of the framework is necessary for realising a DT to meet all the needs of the HBS case and as such could act as a suitable reference framework for practitioners in terms of scope, as it is not overly complex nor too simplistic in nature.

VI. DISCUSSION

Implementing the conceptual framework presented in this paper requires several different technical components. The DT requires several different software services to fully realise a scalable solution, with robust hardware integration. Therefore, further investigation is required to propose actual implementation requirements which at this stage are omitted from the reporting. Notably, the implementation needs to consider the specific HBS case to formulate the requirements and needs. Indeed, with a specific case, a more realistic formulation of requirements can be made, e.g., for the physical aspects of device communication. In future work we aim to apply the framework for a specific HBS implementation to provide further feedback, and by doing so more strictly examine the ISO 23247 suitability. The reason for considering the ISO 23247 standard for the HBS case is partly due to the emphasis on scalability and interoperability [31]. Indeed, an HBS platform by definition needs to be constructed with these concerns in mind for the physical entity, and therefore ISO 23247 is a good candidate as it focuses on similar characteristics.

Another reason to consider ISO23247 is that the standard is a this stage one of the few disseminated standards which has been applied in several real cases (in different domains), indicating a general readiness of the standard. DTs have been proposed for battery systems in recent literature, partly detailed in the background and related work section. However, due to the nature of the HBS case, the existing DTs are hard to apply as they do not emphasise the same concerns as the HBS case. At the same time, there has not been an attempt at mapping a standard-based framework for DTs in the broader battery system domain. As such, applying a standard framework for the HBS case is potentially beneficial for two reasons. First, the standard-based framework can assist in the construction of the DT for the HBS case, and secondly, mapping concerns in the battery domain to the framework can assist practitioner in the broader battery domain due to the carry-over in components. Therefore we expect that this work can facilitate future investigations with the ISO 23247 standard in a broader perspective for battery systems.

VII. CONCLUSION

This paper has presented a first step towards a standard-based reference architecture for digital twins in the complex battery domain. A digital twin is a potential solution to assist in battery observation and control by introducing high-fidelity system models which can be used at run-time or off-line as part of a wider control loop. Notably, a digital twin could improve on several identified challenges related to run-time measurements and control, while offering prognosis capabilities. However, implementing digital twins requires substantial effort, and there is a gap in the literature for a standard digital twin framework in the complex battery system domain. We propose the ISO23247 standard as a candidate to formulate a reference architecture to assist practitioners in future digital twin implementations and confirm the suitability of the standard in a heterogeneous battery system context.

As future work, we are currently working on creating a prototype implementation that adheres to the presented reference architecture to address its practical viability. The prototype will consider a heterogeneous battery system and consist of both a hardware and software implementation in addition to the digital twin.

REFERENCES

[1] R. Zhang and S. Fujimori, "The role of transport electrification in global climate change mitigation scenarios," *Environmental Research Letters*, vol. 15, no. 3, p. 034019, 2020.

[2] Y. Ding, Z. P. Cano, A. Yu, J. Lu, and Z. Chen, "Automotive li-ion batteries: current status and future perspectives," *Electrochemical Energy Reviews*, vol. 2, no. 1, pp. 1–28, 2019.

[3] P. K. D. Pramanik, N. Sinhababu, B. Mukherjee, S. Padmanaban, A. Maity, B. K. Upadhyaya, J. B. Holm-Nielsen, and P. Choudhury, "Power consumption analysis, measurement, management, and issues: A state-of-the-art review of smartphone battery and energy usage," *IEEE Access*, vol. 7, pp. 182 113–182 172, 2019.

[4] S. Muhammad, M. U. Rafique, S. Li, Z. Shao, Q. Wang, and X. Liu, "Reconfigurable battery systems: a survey on hardware architecture and research challenges," *ACM Transactions on Design Automation of Electronic Systems (TODAES)*, vol. 24, no. 2, pp. 1–27, 2019.

[5] A. Badam, R. Chandra, J. Dutra, A. Ferrese, S. Hodges, P. Hu, J. Meinershagen, T. Moscibroda, B. Priyantha, and E. Skiani, "Software defined batteries," in *Proceedings of the 25th Symposium on Operating Systems Principles*, 2015, pp. 215–229.

[6] J. Bergelin, A. Cicchetti, and E. Lundin, "Early validation of heterogeneous battery systems in the railway domain," in *2022 IEEE International Systems Conference (SysCon)*. IEEE, 2022, pp. 1–8.

[7] W. Zhou, Y. Zheng, Z. Pan, and Q. Lu, "Review on the battery model and soc estimation method," *Processes*, vol. 9, no. 9, p. 1685, 2021.

[8] R. Zhang, B. Xia, B. Li, L. Cao, Y. Lai, W. Zheng, H. Wang, and W. Wang, "State of the art of lithium-ion battery soc estimation for electrical vehicles," *Energies*, vol. 11, no. 7, p. 1820, 2018.

[9] J. Groot, *State-of-health estimation of li-ion batteries: Cycle life test methods*. Chalmers Tekniska Hogskola (Sweden), 2012.

[10] M. Nikdel *et al.*, "Various battery models for various simulation studies and applications," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 477–485, 2014.

[11] E. Ferko, A. Bucaioni, and M. Behnam, "Supporting technical adaptation and implementation of digital twins in manufacturing," in *ITNG 2023 20th International Conference on Information Technology-New Generations*, S. Latifi, Ed. Cham: Springer International Publishing, 2023, pp. 181–189.

[12] W. Wang, J. Wang, J. Tian, J. Lu, and R. Xiong, "Application of digital twin in smart battery management systems," *Chinese Journal of Mechanical Engineering*, vol. 34, no. 1, pp. 1–19, 2021.

[13] E. Ferko, A. Bucaioni, P. Pelliccione, and M. Behnam, "Standardisation in digital twin architectures in manufacturing," in *2023 IEEE 20th International Conference on Software Architecture (ICSA)*, 2023, pp. 70–81.

[14] E. Lundin and J. Bergelin, "Heterogeneous battery systems in battery equipped passenger trains," 2021.

[15] P. Wickberg, A. Fattouh, S. Afshar, and M. Bohlin, "Adopting a digital twin framework for autonomous machine operation at construction sites," in *The 7th CAA International Conference on Vehicular Control and Intelligence*, October 2023. [Online]. Available: http://www.ipr.mdu.se/publications/6771-

[16] I. David, P. Archambault, Q. Wolak, C. V. Vu, T. Lalonde, K. Riaz, E. Syriani, and H. Sahraoui, "Digital twins for cyber-biophysical systems: Challenges and lessons learned," in *ACM/IEEE 26th International Conference on Model-Driven Engineering Languages and Systems (MODELS). IEEE*, 2023.

[17] D. Linden, "Handbook of batteries," in *Fuel and energy abstracts*, vol. 4, no. 36, 1995, p. 265.

[18] A. Fotouhi, D. J. Auger, K. Propp, S. Longo, and M. Wild, "A review on electric vehicle battery modelling: From lithium-ion toward lithium–sulphur," *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 1008–1021, 2016.

[19] W. Han, T. Wik, A. Kersten, G. Dong, and C. Zou, "Next-generation battery management systems: Dynamic reconfiguration," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 20–31, 2020.

[20] P. B. L. Neto, O. R. Saavedra, and L. A. de Souza Ribeiro, "A dual-battery storage bank configuration for isolated microgrids based on renewable sources," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 4, pp. 1618–1626, 2018.

[21] W. Waag, C. Fleischer, and D. U. Sauer, "Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles," *Journal of Power Sources*, vol. 258, pp. 321–339, 2014.

[22] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," *Energy storage materials*, vol. 10, pp. 246–267, 2018.

[23] Y. Wang, J. Tian, Z. Sun, L. Wang, R. Xu, M. Li, and Z. Chen, "A comprehensive review of battery modeling and state estimation approaches for advanced battery management systems," *Renewable and Sustainable Energy Reviews*, vol. 131, p. 110015, 2020.

[24] L. Zhang, H. Peng, Z. Ning, Z. Mu, and C. Sun, "Comparative research on rc equivalent circuit models for lithium-ion batteries of electric vehicles," *Applied Sciences*, vol. 7, no. 10, p. 1002, 2017.

[25] N. G. Panwar, S. Singh, A. Garg, A. K. Gupta, and L. Gao, "Recent advancements in battery management system for li-ion batteries of electric vehicles: future role of digital twin, cyber-physical systems, battery swapping technology, and nondestructive testing," *Energy Technology*, vol. 9, no. 8, p. 2000984, 2021.

[26] E. Ferko, A. Bucaioni, and M. Behnam, "Architecting digital twins," *IEEE Access*, vol. 10, pp. 50 335–50 350, 2022.

[27] W. Li, M. Rentemeister, J. Badeda, D. Jöst, D. Schulte, and D. U. Sauer, "Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation," *Journal of energy storage*, vol. 30, p. 101557, 2020.

[28] X. Qu, Y. Song, D. Liu, X. Cui, and Y. Peng, "Lithium-ion battery performance degradation evaluation in dynamic operating conditions based on a digital twin model," *Microelectronics Reliability*, vol. 114, p. 113857, 2020.

[29] P. Runeson, M. Host, A. Rainer, and B. Regnell, *Case study research in software engineering: Guidelines and examples*. John Wiley & Sons, 2012.

[30] ISO 23247, "Automation systems and integration, digital twin framework for manufacturing," 2021.

[31] E. Ferko, A. Bucaioni, P. Pelliccione, and M. Behnam, "Standardisation in digital twin architectures in manufacturing," in *2023 IEEE 20th International Conference on Software Architecture (ICSA)*, 2023, pp. 70–81.