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Cross-Level Impact Analysis (CLIA) Approach for Automotive Battery System: OEM Requirements and Case Study

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Abstract

Traction battery systems for electrified vehicles currently on the market employ primarily lithium-ion batteries (LIBs). In light of increasing system complexity and rapid technological evolution, the automotive industry faces challenges in adequately integrating next-generation battery technologies to meet the stakeholders' requirements. To support future battery system development, early-stage understanding of the upcoming battery technologies and their impact on higher-level subsystems (module, pack, system) is critical. Existing battery development methods remain domain-specific and fragmented across system hierarchies, lacking holistic consideration from cell chemistry, higher-level (sub)systems up to the vehicle level. Meanwhile, current Systems Engineering (SE) approaches lack specialized application for cross-disciplinary impact analysis in battery systems [1]. We propose the Cross-Level Impact Analysis (CLIA) framework, a Model-Based Systems Engineering (MBSE) framework using SysML for systematically modelling dependencies within the battery system and tracing property changes across (sub)systems. To address real-world challenges, integrating frontline OEM perspectives is crucial. Specifically, in-depth discussions with Chinese OEMs are conducted to identify the key requirements for cross-level impact analysis for automotive battery systems. To assess how well the current CLIA approach can fulfil the identified requirements, a comprehensive case study demonstrates CLIA application to quantify the extent of impacts: Changes in anode thickness were traced to cell-level performance (lifetime and capacity), with results aligning with published experimental data. This paper shows the potential of the CLIA approach to prospectively investigate impacts of future battery technology generations and provide strategic decision-making foundations for battery technology roadmaps. Future work will verify CLIA through industrial use cases, focusing on practical deployment of the CLIA to derive boundary conditions for Next-Gen battery system design considering a future battery technology (e.g. all-solid-state battery) with an industry partner to demonstrate and evaluate its applicability and usability.

Keywords: Battery System; Battery Technology; Impact Analysis; Systems Engineering (SE); Model-Based Systems Engineering (MBSE)

1. Introduction

Traction battery systems of electrified vehicles currently on market employ primarily lithium-ion batteries (LIBs). However, the upward trend in electromobility is placing increasing demands on battery cells. The global demand for LIBs regarding electric mobility is projected to grow exponentially, reaching up to 4–5.5 TWh annually by 2030, which is up to eight times compared to the figure in 2023 [2,3]. In addition to increasing performance and reducing costs, increasing the reliability as well as sustainability of battery cells is of great importance.

This leap to more reliable, high-performance and sustainable battery cells could be realized by introducing and implementing future cell chemistries that are currently still undergoing research. In addition to investigating the foundational materials (cathode, anode, electrolyte, and separator) and prospective cell configurations for Li-based batteries, as highlighted in the work of Song *et al.* [4], researchers are exploring alternative battery chemistries and innovative concepts as well, such as those involving sodium- / potassium-ion [5], calcium-ion [6], magnesium-ion [7] and aluminum-ion [8].

For the automotive industry in particular, the lack of knowledge regarding the new technologies of electrochemical

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energy storage in the powertrain poses a major challenge [9]. Each of these potential cell chemistries may pose completely different and volatile requirements on the design of the battery cell and its higher-level system [1]. To identify needs and develop new methods supporting the product development processes during this technology change, it is important to understand and clarify the future potential of the subsequent battery technologies and their effects on the higher-level system at an early stage.

2. State of the Art

Based on the requirements for vehicle performance, the design process of a battery system typically begins with estimating the necessary system specifications, such as (dis)charge rates, energy capacity, or durability, which then narrow down the choice of suitable cell types. The subsequent concept layout and detailed design steps are carried out based on this cell selection.

During the detailed design phase, a variety of mathematical and simulation models are used to estimate key system properties, such as energy density or thermal behavior. These models help determine whether electrical, thermal, mechanical, and other domain-specific requirements are met. However, they generally do not capture how cell chemistry parameters or cell-level specifications influence higher-level subsystems. Investigations of cross-level interactions in battery systems generally rely on domain-specific models and analyses, each of which requires deep expertise in the respective discipline. At the same time, studies examining how battery cells influence higher-level subsystems are often limited to specific cell formats or technologies.

To understand the implications of future battery technologies at an early stage of product development as well as achieve a holistic view, transdisciplinary and integrative approaches such as MBSE are considered. MBSE is a structured approach that utilizes interconnected cross-domain system models to assist in the management of system requirements, design, analysis, verification, and validation [10]. MBSE rests upon three main pillars: Modeling Language, Modeling Tool, and Modeling Method.

Engineering Change Management (ECM) is also a relevant practice to assist trace property changes across (sub)systems. ECM refers to the systematic approach of organizing, controlling, and implementing Engineering Changes (ECs) within a product lifecycle [11]. An approach to predict effort and risk of engineering changes is described by Albers *et al.* [12] using the example of an automotive wiring harness. Based on the model of System Generation Engineering – SGE [13,14], engineering changes are characterized as carryover, attribute and principle variations of reference system elements, based on which a trend of effort and risk is derived.

There are also existing approaches that applied MBSE to assist ECM. Wilms *et al.* [15] presented an approach to assess change propagation across domains and products in product model using MBSE. In the proposed ECM product model, different views (functional, structural and change analysis view) are created using the defined elements and linkages. Martin *et al.* [16] proposed a model-based ECM method that enables iterative, holistic analysis of change propagation and impacts in complex systems. By systematically validating change requests, modeling propagation pathways and documenting change information, this method supports the agile decision-making in MBSE environments.

Before the authors work, no MBSE approach has been identified that is applied to battery systems and specifically focuses on assessing how expected changes in battery chemistry properties affect the properties of higher-level subsystems (cell, module, pack, and battery system). In the previous work [1], the authors identified the need for such a methodology and proposed the Cross-Level Impact Analysis (CLIA) framework, a Model-Based Systems Engineering (MBSE) framework using SysML for systematically modelling dependencies within the battery system and tracing property changes across (sub)systems.

3. Methodological Approach

Figure 1a) provides the overall research process for developing the CLIA approach. Further methodological details can be found in [1].

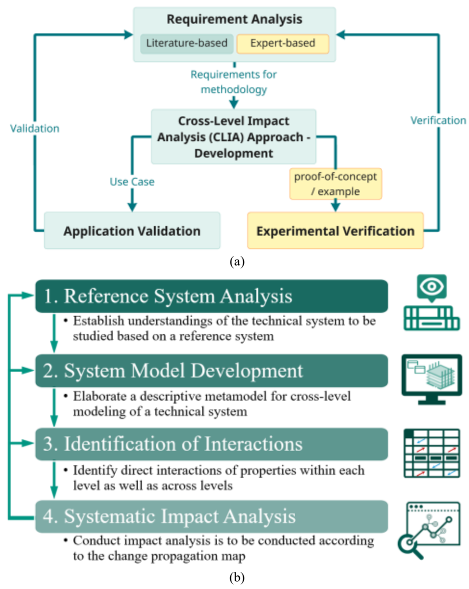

Fig. 1. a) Overview of research and the focus of this paper (highlighted) and b) Outline of the CLIA Approach (according to [1])

In our previous work, we defined the initial System of Objectives based on literature-derived requirements, which corresponds to the activities shown in Figure 1a). In the present paper, the focus shifts to conducting the initial expert-based requirement analysis, eliciting requirements from OEMs (Section 4), and performing a proof-of-concept study to preliminarily verify these requirements (Section 5).

The steps of the CLIA Approach, outlined in Fig. 1b) and developed in prior work, can be briefly summarized as follows:

(1) **Reference System Analysis:** Establish an understanding of the technical system under study using a reference system, considering particularly its hierarchical structure.

(2) **System Model Development:** Develop a descriptive metamodel for cross-level system modeling and the system

architecture of the battery system based on the reference system from Step 1.

(3) **Identification of Interactions:** Identify and structurally model both intra-level and cross-level interactions between system properties according to defined interaction patterns.

(4) **Systematic Impact Analysis:** Conduct an impact analysis using a change propagation map, beginning with the initial property change(s) and considering the relevance of all intra- and cross-level interactions among system elements.

4. Expert-Based Requirement Analysis

4.1. Interview setup

Selection of experts for the initial study was carried out through an outreach process, guided by multiple criteria. To ensure a representative view despite the small initial sample size, the expert selection was aimed at representing a possibly broad range of stakeholder perspectives. The selection includes specialists working at different levels of the battery value chain, ranging from cell and module development to overall system integration. The experts shall be employed in different types of OEMs, including established national OEMs with a strong domestic market presence, joint venture OEMs, emerging OEMs, and international leading OEMs, with varying product portfolios and development strategies. The experts shall have more than five years of industry experience, except those who work in an emerging start-up. Each expert shall also have leadership responsibilities within their development team to ensure that the collected input reflects both technical expertise and an understanding of process- and organizational-level considerations.

Invitations were sent to the selected 14 experts from different OEMs. Six responses were received, of which experts from three OEMs confirmed their participation in the initial study. In the following, they are referred to as Expert A, B, and C, with their corresponding information provided in Table 1. To preserve the respondents' anonymity, their names and affiliations are not disclosed in this study.

Table 1. List and corresponding information of the experts for the initial study

Expert	Role / Function	OEM Type	Market	Product Portfolio*	Industry Affiliation
A	Lead of cell chemistry team	National; Independent / Joint Venture	China	M	>5 yrs
B	Lead of battery system R&D department	Global; Independent	China	M / N	>5 yrs
C	Lead of battery system R&D team	Emerging; Independent	China	L	<5 yrs

* Classification according to UNECE [17] categories (M = passenger cars, N = goods vehicles, L = two- and three-wheelers and quadricycles)

The three experts were interviewed through both onsite and online meetings. The interviews followed a free-discussion format while guided by the pre-established interview guide presented in Table 2. The researcher acted as both the active interviewer and the note-taker. The notes taken during the interviews form the basis for the subsequent analysis.

Table 2. Interview guide: aspects, objective and leading questions.

Aspect	Objective	Leading question
Application Scenario	Understand the **context of use**: where, how, and by whom the CLIA Approach will be applied.	At which battery system development stage within your company could this approach be applied?
Application Prerequisites	Identify **preconditions** before CLIA Approach can be applied.	What are the prerequisites for applying this approach in actual R&D process?
Function & Feature	Capture **what the CLIA Approach must do** (tasks, actions, behaviors) and define its **distinctive attributes or characteristics.**	What additional functions / features should the approach possess?
Value	Assess the **benefits realized** when requirements are fulfilled.	What added value does the CLIA Approach provide?

4.2. Interview summary and discussion

To structure the discussion on **Application Scenarios**, we referred to a generic phase model of battery development, which was reviewed with the interviewees: *Technology Foresight*, *System Requirement Definition*, *Concept Design*, *Simulation & Analysis*, *Subsystem Testing & Verification* as well as *System Testing & Verification*. While all three experts acknowledge most stages of the battery development process, their emphasis and level of integration vary considerably. *Technology Foresight* is systematically integrated only by expert B and C. *System Requirement Definition* shows notable differences: expert A relies on requirement breakdown and supplier matching without unified management, expert B emphasizes whole-vehicle requirement, and expert C follows a client-driven approach with flexible formats. *Concept Design* and *Simulation* are consistently addressed across all experts with varying levels of detail. Prototyping emerges as less uniformly described, being explicitly included only by expert C, as expert A and B mainly work with supplier considering cell level. *Testing and Verification* are generally emphasized, though Expert B does not explicitly mention system-level testing. Overall, the findings suggest a shared structure in the development process but highlight different practices and degrees of formalization across organizations.

When asked at which stage of the battery system development process the proposed CLIA approach could be applied, Expert A identified application potential across the *Concept Design*, *Simulation & Analysis*, and *Subsystem Testing & Verification* (Stages 3–5). In contrast, Expert B limited applicability to *Concept Design* (Stage 3) only. Expert C highlighted both *Concept Design* and *Simulation & Analysis* (Stages 3–4) as suitable points of application. Taken together, the responses suggest that *Concept Design* (Stage 3) is consistently regarded as the primary entry point across organizations, while subsequent stages are considered applicable depending on the company's practices and level of process formalization.

The interview discussions regarding **Application Prerequisites** as well as **Function & Feature** were initiated using the requirements derived from the literature analysis conducted in our previous work [1]. These are summarized in Table 4. While many of the requirements previously reported in the literature were confirmed, not all of them were consistently mentioned across the experts interviewed. For example, requirements such as *Support for hybrid chemistry battery systems* were not referenced by any of the experts. In addition, several new requirements emerged, representing newly identified perspectives from industry practice. These findings should be regarded as an initial set of industrial requirements, as the limited number of experts consulted does not allow for broad generalization at this stage.

5. Proof of Concept – Illustrative Example

A proof-of-concept was conducted to assess how well the current CLIA approach can fulfil the identified requirements, as well as to identify gaps or limitations in this course. To examine this, three engineers from our development team were involved, as they possess detailed system knowledge within the existing modeling environment to efficiently carry out iterations and refinements.

Changing cell chemistry implies changes in a certain set of properties of the subsystems at the cell chemistry level. To demonstrate the feasibility of the CLIA approach (cf. Fig. 1b)), we present a literature-based illustrative example considering a simplified case focusing on the impact analysis of one changed property. It is intentionally limited to the cell level as well to isolate and clarify foundational interactions before scaling to multi-level complexity.

For such an illustrative example, we refer to the experiment conducted in the work of Kim et al. [18]. Detail information needed for the illustrative example case study is extracted and presented in Table 3.

Table 3. The data from [18] used for the illustrative example.

Influencing property: **anode thickness**	Influenced property: **battery cell lifetime*** (one month aging test at 25°C, experimental results)			Influenced property: **battery cell capacity** (experimental results)
	Indicator 1	Indicator 2	Indicator 3	
124 µm	0.016 V	0.015 mm	97.43%	100%
135 µm	0.015 V	0.017 mm	98.67%	102%
146 µm	0.017 V	0.016 mm	100%	102%

*Indicator 1: Deviation of OCV between aged and new batteries
Indicator 2: Deviation of cell thickness
Indicator 3: Recovery ratio of battery cell capacity

The purpose of the work of Kim et al. [18] is to investigate the effect of the areal capacity ratio of negative to positive electrode (N/P ratio) on the electrochemical properties with the LIB, where the N/P ratio is controlled by keeping the cathode thickness constant and only adjusting the anode thickness with a fixed anode density. In these experiments, the change of electrochemical properties of the LIB, specifically the battery cell capacity as well as three indicators of battery cell lifetime, was observed when changing the thickness of the anode.

5.1. Interactions between properties of the system elements

Interactions are identified primarily through extensive literature review [19–30], physical relationships, as well as prior experiences of the authors. As for the literature review, we specifically reviewed papers that examined relationships either within a single subsystem (e.g., the impact of module interconnect resistance on module lifetime as in [22]) or across subsystems (e.g., the influence of electrode thickness ratio on battery cell capacity as in [18]). The papers that we included can be either Validation Research, which investigates novel techniques not yet applied in practice; Evaluation Research, which demonstrates and assesses techniques implemented in practice; or Solution Proposal, which suggests new or enhanced approaches to a specific problem. An excerpt of the created parameter-based Design Structure Matrix (DSM) can be seen in Fig. 3. The correlation direction determines what the outgoing property has an influence on. For instance, "*Property A →Property B*" indicates that *Property A* has an influence on *Property B*. A positive or negative interaction specifies whether an improvement/increase in *Property A* leads to a change in the same direction in *Property B* or in the opposite direction (i.e., a deterioration/decrease). The non-positive/non-negative correlation indicates that the changing direction is either unclear or cannot unambiguously determined. The numbers inside the matrix indicate how many interactions exist between properties of the (sub-)systems shown in the row and column.

Table 4. Overview of the accessed requirements: Application Prerequisites and Function & Feature (✓: mentioned explicitly; ○: implied implicitly; ✗: not mentioned). The cross-hatched requirements represent those newly identified in this study.

Aspect	Requirement	Expert A	Expert B	Expert C
Application Prerequisites	(Semi-)quantitative evaluation	✓ – results must be quantitative	✓ – emphasized as valuable	✓ – required for application
	Interface with common software	✓ – interfaces needed	✗	○
	Linkage with vehicle-level requirements	✓	✓	○ – not necessarily full vehicle requirements
	Applicability to new chemistries	✓ – must be flexible for exploring new electrochemistry	○ – mostly minor rather than major chemistry changes	✗
Function & Feature	Support for hybrid chemistry battery systems	✗	✗	✗
	Reuse information from previous change cases	✓ – reuse past criteria and information of earlier product generations	○ – considering historical baseline adjustments	✗
	User-friendly UI	✗	✗	○
	Transparent analysis & calculation process	✓ – results must be explainable, with influencing factors shown	✓ – intuitive predictions and feedback needed	✓ – export of all design changes consequences needed
	Verifiability of results	✓ – results must be verifiable	○	○
	Add/Re-weight evaluation criteria	✗	✗	○
	Version management	✓ – version management of results	✗	○
	Modular combinability	✓ – modules of the approach should work independently or in combination	✗	✗
	User-defined modules	✓ – customization shall be supported	✗	✗
	Predictive guidance design adjustment directions	✗	✓ – predictive design adjustment directions required	○
	Intuitive feedback (trade-offs, minimal impact, Comparison of pros/cons)	✗	✓ – system should provide intuitive trade-off feedback	✓ – Comparison of pros/cons of different design options

The interactions captured in the matrix above are then visualized in a Relationship Map Diagram (RMD) in such a way that the change propagation of anode thickness, i.e. the change triggering property, can be seen all the way to the influenced properties to be investigated - battery cell capacity as well as battery cell lifetime. As shown in Fig. 4, the complexity of the interactions is already noticeable, even when considering a simplified case.

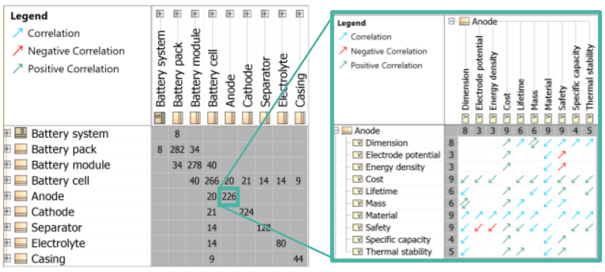

Fig. 2. Excerpt of the identified interactions between the properties of the system elements.

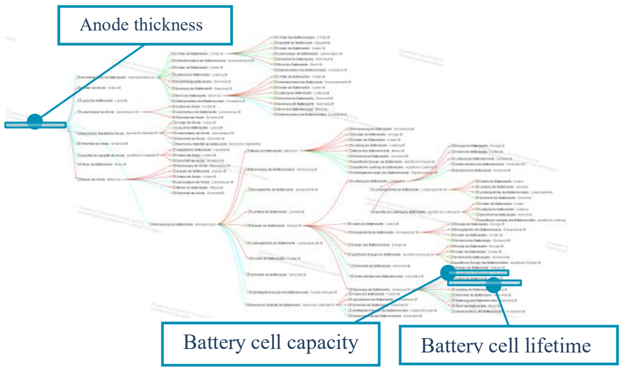

Fig. 3. RMD showing the interactions between the properties of the system elements for the case study with anode thickness as the only change triggering property, whose impact on battery cell capacity as well as battery cell lifetime are to be investigated.

5.2. Implementation of systematic impact analysis

The three engineers involved with technical expertise in battery system development conducted the Systematic Impact Analysis according to Fig. 1b). Firstly, each engineer assesses the *Degree of Change* of the initial property, which is the change of anode thickness from 124 µm to 135 µm / 146 µm. These subsequently affect the *Degree of Change* of all other properties according to Fig. 3. Afterwards, each engineer evaluates the *Relevance of Interaction* considering *Degree of Change* of the influencing property and the influenced property at the same time. For example, when rating the impact of operating temperature of the battery cell on the battery cell power, a medium increase of the operating temperature might improve the cell power, while a significant increase of the operating temperature will result in a decrease in cell power. *Degree of Change* of the intermediate properties are calculated automatically when the corresponding *Relevance of Interaction* is rated. The process continues until the end of the RMD is reached. In the last step, the engineers assess the *Degree of Change* of the properties to be investigated, that is the indicators of battery cell lifetime, e.g. open circuit voltage (OCV) difference, and battery cell capacity (see Table 3.). This is used to compare the calculated results of *Degree of Change* using the CLIA Approach (calculation formula as in [1]).

5.3. Result comparison

The *Degree of Change* in battery cell capacity and lifetime is respectively calculated (cf. Section 5.2.) and evaluated by engineers based on the experimental results of these changes. The results are shown in Table 5.

Table 5. Comparison of accessed *degrees of change* in the illustrative example - evaluated based on the experimentally measured data shown in Table 3. and calculated with the CLIA approach described in Section 5.2.

Influencing property:	*degrees of change* Influenced property: **battery cell lifetime***		*degrees of change* Influenced property: **battery cell capacity**	
anode thickness	Evaluation based on results in Table 3	Calculated results using CLIA	Evaluation based on results in Table 3	Calculated results using CLIA
124 µm	-	-	-	-
135 µm	0.140	0.060	0.160	0.128
146 µm	0.270	0.093	0.160	0.185

For the battery cell capacity, the *Degree of Change* determined with the two ways shows a very good agreement. For the battery cell lifetime, the calculated results using CLIA show a slightly lower *Degree of Change*. One of the reasons for the difference between two affected properties is that the battery cell lifetime is difficult to measure directly and can only be interpreted based on the indicative parameters. Moreover, the aging test in [18] is performed for one month with less than 80 charge cycles. This does not correspond to the common definition of battery cell life (normally more than 300 cycles or more than two years), which is however considered by the engineers when performing the impact analysis.

The evaluated results can serve the purpose of showing the extent of the impact of a property change, which proves the applicability of the proposed CLIA approach.

6. Conclusion & Outlook

In this paper, we identified the initial key requirements through in-depth discussions with Chinese OEM experts and applied the CLIA approach to analyze cross-level impacts in automotive battery systems. We carried out a proof-of-concept study analyzing the impact of anode properties on two cell properties. While this example does not encompass the cross-level scope, it highlights key steps to quantify property changes as well as to demonstrate the extent of their impact, providing a foundation for future cross-level extensions.

This paper therefore demonstrates the potential of the CLIA approach to prospectively investigate the impacts of future battery technology generations and to provide a foundation for strategic decision-making in battery technology roadmaps. This is supported both by statements from OEM experts and by the comprehensive proof-of-concept example.

Future work will focus on three main aspects. Regarding requirement engineering, further in-depth interviews with additional Chinese and German OEMs are planned to confirm the requirements identified in this study. Furthermore, the CLIA model will be refined according to newly identified

OEM requirements, enabling impact analyses across multiple levels of the battery system. Based on this, future case studies will investigate how changes in next-gen cell chemistry properties affect system-level performance. Given the limited availability of data for emerging battery technologies, these studies may require the design of experiments for specific scenarios. As for validation, the approach will be verified through industrial use cases to derive boundary conditions for next-generation battery system design. Collaboration with industry partners, for example on all-solid-state batteries, is planned to evaluate the applicability and usability of the CLIA approach in real-world context.

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