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Systematic Model Design for Determining Interoperability Requirements Based on Technology in EMSB

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Abstract

This study aims to develop a systematic framework for defining interoperability requirements within the Electric Motorcycle Swappable Battery (EMSB) ecosystem by applying the FACTS methodology and Dynamic Open Innovation. The proposed model integrates stakeholder engagement, technical standards analysis, and validation to establish interoperability across information, function, and business layers. Using a confirmatory factor analysis and structural equation modeling approach, the model was empirically validated through expert input from key EMSB stakeholders in Indonesia. Results reveal acceptable model fit, with significant explanatory power across interoperability constructs. Findings emphasize the need for cross-brand standardization and stakeholder collaboration to support EMSB infrastructure development. This research contributes to both theory and practice by offering a validated model that aligns technical, organizational, and institutional dimensions of interoperability. It also provides strategic insights for policymakers and practitioners in implementing effective standardization strategies. Future research should explore model extensions by incorporating regulatory flexibility, cybersecurity measures, and cross-national comparisons to enhance the applicability of the interoperability framework in diverse contexts.

Keywords
Interoperability, Electric Motorcycle, Battery Swapping System, Open Innovation, Standardization Framework

1. Introduction
Activities within the digital supply chain entail the advancement of information systems and the adoption of the latest technologies (Fahma et al., 2024). Industry 4.0 adoption has been shown to significantly enhance digital supply chain integration, innovation, and visibility, collectively improving overall supply chain performance (Khan & Emon, 2025).

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Big data analytics and Internet of Things (IoT) are enabling the development of sustainable strategies by supporting supply chain processes, decreasing operational costs, and enabling better control and monitoring of operations (Stroumpoulis & Kopanaki, 2022).

Interoperability is indeed a critical factor in the successful integration of technologies in Industry 4.0. The interconnected nature of Industry 4.0 systems requires seamless communication and data exchange between various components, technologies, and systems (Bousdekis & Mentzas, 2021). The need for interoperability extends across multiple levels of integration, including connection, communication, coordination, cooperation, and collaboration (Sanchez et al., 2020). It enables the creation of smart factories, intelligent manufacturing environments, and cyber-physical systems that can adapt, communicate, and make decisions in real-time (Lampropoulos et al., 2019; Ryalat et al., 2024).

Therefore, this study focuses on a case involving electric motorcycles equipped with swappable batteries (EMSBs). In 2019, the Indonesian government initiated an Electric Vehicle (EV) acceleration program (Fahma et al., 2024). The Indonesian government targets to have 13 million electric motorcycles in Indonesia by 2030. This target is expected to be supported by an adequate number of Public Electric Vehicle Charging Stations (SPKLU), totaling 32,000 units (Cholandha, 2025). The lack of a comprehensive recharging network and the high purchase price of EV are the main obstacles to adoption (Broadbent et al., 2019).

Swappable batteries (SB) are indeed a promising innovation as an alternative recharging solution for EV. Battery swapping technology offers several advantages over traditional plug-in charging methods, including significantly reduced charging times and improved operational efficiency for EV fleets (Ding et al., 2021). The battery swapping approach allows EVs to replace depleted batteries with fully charged ones in a matter of minutes, similar to refueling at a gasoline station (Ahmad et al., 2020). This system addresses two major challenges in EV adoption: limited battery capacity and long charging times (Kang et al., 2016).

Currently in Indonesia, electric motorcycles circulate with varying battery specifications, restricting users to swapping batteries only at Battery Swapping Stations (BSS) specific to each brand, which leads to inefficiencies in the energy supply chain due to the high investment required for batteries and BSS. This situation contradicts the potential benefits of a well-designed battery swapping system, which can provide flexibility and efficiency in distribution systems (Alharbi et al., 2022). Therefore, promoting a battery swapping ecosystem that is interchangeable and interoperable across brands is crucial, necessitating the development of interoperability standards to ensure cross-brand collaboration in the charging process (Fahma et al., 2024). This approach aligns with the concept of a multiregion battery swapping-charging network model, which emphasizes the importance of efficient and collaborative management of BSSs located in different regions (Liu et al., 2020).

The development of interoperability requirements through standardization in the early stages of EMSB supply chain engineering aims to minimize investment costs, expand the market by providing certainty and ease of energy supply to consumers, enabling EMSB technology to succeed in the market and avoid the valley of death, while simultaneously promoting innovation by establishing technical specifications, protocols, and standard interfaces that facilitate collaboration, information exchange, and integration among systems and products (Fahma et al., 2024). Global collaboration must be encouraged to establish universal standards and interoperability among charging systems in order to promote widespread adoption of EV (Zentani et al., 2024).

In the development of standards, the National Institute of Standards and Technology (NIST) under the U.S. Department of Commerce introduced the Framework for Analysis, Comparison, and Testing of Standards (FACTS) (Witherell et al., 2013). Several standards developed using this framework include battery status data format, standardization of system service functions, real-time battery condition monitoring, payment systems, and tariff schemes. FACTS is presented as an approach for developing standards, particularly in the context of EV (Khalid et al., 2019). FACTS framework was chosen because it is capable of formalizing and organizing information to accommodate the needs of various stakeholders in a more consistent and effective manner (Witherell et al., 2013).
The standard development approach using the FACTS framework shares similarities with the concept of open innovation, as both emphasize the importance of transparent processes and multi-stakeholder involvement. In this context, standardization bodies need to engage external stakeholders such as manufacturers, regulators, relevant authorities, consumers, suppliers, academics, and researchers. The active participation of all stakeholders is essential

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to integrate knowledge, expertise, resources, and innovative ideas into the standard-setting process. The connection between standards and open innovation lies in the principle that standards can be improved, adapted, and strengthened through external input, diverse perspectives, and collaborative approaches core elements of open innovation.

The dynamic nature of open innovation is reflected in the ability of standard developers to adaptively recognize and respond to changes in the external environment. Therefore, the standard development process not only accommodates existing standards but is also capable of tracking technological advancements and identifying emerging trends and opportunities. This requires proactive engagement with external partners, adjustment of innovation strategies, and the utilization of new sources of knowledge and expertise.

In some cases, different processes of stakeholder engagement affected the number, identity, and age of stakeholders involved, as well as the variation and quality of the resulting standards (Rawhouser et al., 2017). The benefits of standard implementation and stakeholder engagement extend beyond the development phase and improve the implementation of evidence-based interventions in clinical settings (Gilliam et al., 2002; Holcomb et al., 2021). Adopting ISO can positively impact financial performance (Chakroun et al., 2019). This study employs the ISO Methodology to estimate the impact of interoperability standards and requirements. The ISO approach is chosen due to its straightforward methodological steps and robust tools. Moreover, the ISO Methodology guarantees a rigorous and internationally recognized standardization process. This methodology has been proven effective across various companies and industrial sectors in assessing the contribution of standards to their performance.

Therefore, this study is aimed at designing interoperability requirements for EMSB by utilizing a dynamic open innovation approach. This paper presents an innovative concept on the application of dynamic open innovation in the development of product standards, particularly for smart connected products. Additionally, the study proposes an economic model relevant to smart connected product companies within the EMSB ecosystem, resulting from the implementation of standardization supported by an open innovation strategy. Through this approach, the research seeks to design a systematic model for determining interoperability requirements at the information, functional, and business layers based on technology in EMSB. The findings of this study are expected to provide strategic considerations for national standardization bodies in setting priorities for EMSB-related standard regulations.

2. Research Model

The steps in this stage utilize the FACTS, integrated within the framework of Dynamic Open Innovation. The development of EMSB interoperability requirements is carried out through the FACTS methodology, which consists of four main steps: identification of technical needs, technical analysis, standards comparison, and standards testing. These stages are structured within the dynamic open innovation framework, which organizes the process into three core streams: the inbound process (gathering technical requirements and data from stakeholders), the interaction process (collaboration and refinement of technical information among parties), and the outbound process (final formulation and validation of interoperability requirements).

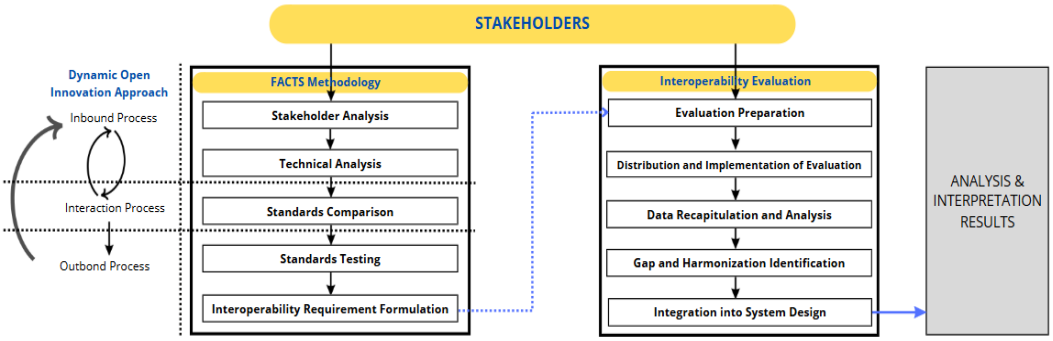

Figure 1. Proposed research model

The proposed research model, as illustrated in Figure 1, is developed to enable a comprehensive and stakeholder-driven design of an interoperable Battery Swapping System (BSS). The framework integrates the FACTS

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methodology with a simulation-based design approach under the paradigm of Dynamic Open Innovation (DOI). The model is structured into two main components: a methodological evaluation layer and an application design layer. At the top level, the FACTS methodology guides a systematic process consisting of five sequential activities: need identification, technical analysis, standard comparison, standard testing, and formulation of interoperability requirements. These activities are informed by multi-stakeholder perspectives and are aligned with the 5W1H principles of the Zachman Framework to capture diverse viewpoints across technical and organizational domains.

To ensure that the interoperability requirements derived from the FACTS analysis are practically valid and contextually appropriate, an Interoperability Evaluation module is introduced. This module involves stakeholders not only as information providers but also as active assessors. The evaluation follows a structured sequence: preparation, deployment, data analysis, gap and harmonization identification, and integration into system design. This feedback loop is essential to validate that information-layer interoperability flows effectively into functional and business processes, ensuring that the resulting system can operate across different vendors, platforms, and regulatory standards. The bottom part of the framework is the system design phase, where the visible interoperability is developed through three sub-processes: design requirement identification, concept development and selection, and prototyping. Design inputs are derived from the voice of customer, business, and technology, synthesized into technical requirements. These are used to generate and evaluate multiple conceptual alternatives, with expert judgment applied to select the optimal design. The prototyping process then defines system specifications, constructs architecture based on the Rapid Application Development (RAD) model, and builds the system using an Interoperability-Oriented System (IOS) approach. The completed system is validated through black-box testing before being implemented in the BSS simulator.

3. Methodology

3.1 Study Procedure and Measures

This study employed a structured assessment instrument grounded in the FACTS methodology to evaluate interoperability across stakeholders within the EMSB ecosystem. The instrument integrated stakeholder analysis, technical assessment, standards comparison, and conformance evaluation using the Zachman Framework as a conceptual base. It specifically examined three layers of interoperability (information, function, and business) across key actors including manufacturers, infrastructure operators, system developers, government agencies, and financial service providers.

Data were collected through a structured questionnaire distributed to selected experts using purposive sampling, targeting those actively involved in EMSB infrastructure. The instrument included five sections covering interoperability alignment, functional-business model support, standardization gaps, harmonization priorities, and open-ended recommendations. Items were rated on a five-point Likert scale, while standard gaps and harmonization priorities were classified categorically. Prior to deployment, the instrument was validated by domain experts to ensure relevance and clarity, leading to refinements aligned with real-world EMSB implementation. Final data were gathered through focused group discussions and direct correspondence, enabling both quantitative and qualitative analysis of interoperability and standard conformance in Indonesia's EMSB ecosystem (Table 1).

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Table 1. Measurement items

Constructs	Measurement Item	Source
Information to Function Interoperability (IFI)	Operational decisions (e.g., authentication, scheduling, charging) rely on integrated user and battery data (IFI1)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Data formats across vendors are sufficiently consistent for SPBKLU system integration (IFI2)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Backend systems successfully translate real-time information into functional system responses (IFI3)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Communication protocols enable seamless data exchange between backend infrastructures (IFI4)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
Function to Business Interoperability (FBI)	Core system functions improve the operational efficiency of SPBKLU infrastructure (FBI1)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Interoperability fosters collaboration across different battery swap service providers (FBI2)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Functional capabilities enable fair revenue-sharing models within the EMSB ecosystem (FBI3)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	The system supports integration with ancillary services (e.g., digital payment platforms, mobility systems) (FBI4)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
Perceived Interoperability Gaps (PIG)	Misalignment exists between system functionalities and business standard expectations (PIG1)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Industry actors face challenges in interpreting and implementing interoperability standards (PIG2)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Institutional support from standard-setting bodies and regulatory stakeholders requires reinforcement (PIG3)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
Standard Harmonization Needs (SHN)	Harmonization is critically needed at the information layer (e.g., SOC data, usage logs) (SHN1)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Harmonization is required for technical functions (e.g., charging, swapping, monitoring) (SHN2)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Harmonization is essential for business processes (e.g., authentication, tariff sharing, partnerships) (SHN3)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Harmonization should address institutional roles and stakeholder governance (SHN4)	Witherell, et.al. (2013) & Kirpes et.al. (2019)
	Harmonization is needed for communication protocols between backend systems (SHN5)	Witherell, et.al. (2013) & Kirpes et.al. (2019)

3.2 Sample

The data collection for this study utilized a purposive sampling strategy targeting stakeholders directly involved in the electric motorcycle ecosystem in Indonesia, specifically focusing on the interoperability of swappable battery charging stations. A total of 20 key stakeholders were selected for participation, comprising representatives from electric motorcycle and battery manufacturers, backend communication system developers, government regulators, energy distributors, financial institutions, certification agencies, and academic researchers. These respondents were invited to participate in a structured Focus Group Discussion (FGD) to evaluate the technical and institutional alignment of existing interoperability standards using the FACTS approach.

Participants were required to have domain-specific knowledge or authority over standard development, implementation, or policy making in the EMSB ecosystem. Out of the 20 invited participants, all completed the instrument in full, providing valid and analyzable responses. The evaluation involved rating the adequacy of data flow from information to function, and from function to business processes, as well as identifying perceived gaps and recommending standard harmonization needs across five interoperability layers: information, technical function, business processes, institutional structure, and communication protocols (Table 2).

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Table 2. Respondent

Stakeholder		Description	Respondents	Freq.	Percentage
Primary	Researchers	Researchers conducting studies at Centers of Excellence (PUI) and national research institutions	PUI Battery UNS, BRIN	2	10%
	EV and Battery Manufacturers	Electric motorcycle manufacturers	Volta, Polytron	2	10%
	BSCS Operators, Technology and Information Systems Provider	Physical provider of charging, battery swapping stations, API integration, IoT management platforms, and data services	Swap Energy, Oyika	2	10%
	Government Regulators	Establishing regulatory standards for battery and infrastructure interoperability (including dimensions, communication protocols, and safety)	Dirjen EBTKE, Dirjen Aptika	2	10%
		Establishing regulations and standards for the National Payment System, and granting licenses as well as supervising banks involved in the integration of BSCS payments	Bank Indonesia, OJK	2	10%
	Financial & Transaction Agents	Managing user balances and providing a direct payment system for battery swap transactions	GoPay, OVO	2	10%
		Enabling backend infrastructure to facilitate virtual account management, automatic debits, and settlement between BSCS partners	BRI, BCA,	2	10%
		Overseeing the integration of the payment system with the backend infrastructure of BSCS and battery service operators	Midtrans, Xendit	2	10%
Supporting	Academia	Academics who have conducted research on the business systems of charging stations	UNS, UGM, POLINES, TEL-U	4	20%
Total				20	100%

Based on the Table 2, benchmarking will be conducted by comparing stakeholder involvement in the battery swapping and charging station system in Indonesia with similar cases in other countries. In the Indonesian context, stakeholder participation appears to be diverse and can be categorized into three main groups: providers of technology and physical infrastructure, government institutions acting as technical and payment system regulators, and providers of digital transaction services and backend infrastructure. In addition, academic researchers from national institutions and universities contribute through studies on the business models and technologies underpinning the BSCS system. This pattern reflects an integrated ecosystem, and benchmarking against international cases will provide insights into the effectiveness of cross-sectoral collaboration and the readiness of interoperability standards and payment systems in supporting the acceleration of electric vehicle adoption (Table 3).

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Table 3. Stakeholder Benchmarking

Stakeholder	Interoperability Layer			Comparative Stakeholder	Involvement
	Info.	Func.	Busi.		
EV and Battery Manufacturers	√	√		BYD (Yuan, et.al. 2024), TOGG (Mordue, et.al. 2022), Hero Electric (Hemavathi, et.al. 2021)	Manufacture EVs with standardized battery packs; collaborate with BSCS operators to ensure interoperability of battery dimensions, voltage, and BMS.
BSCS Operators, Technology and Information Systems Provider	√	√		NIO (Pisano, et.al. 2023), ZES (Akgün, et.al. 2024), RACE Energy (Hema, et.al. 2022)	Develop and manage swap infrastructure, BMS integration, mobile interfaces, IoT-enabled tracking, cloud platforms, and auto-routing APIs for battery allocation and health diagnostics.
Government Regulators	√	√	√	MIIT, Bank of China (Cao, et.al. 2022), EMRA, TCMB (Sirin, et.al. 2022), Ministry of Power, Bank of India (Majid, et.al. 2024)	Define battery standardization, data-sharing protocols, and battery infrastructure payment.
Financial & Transaction Agents			√	ICBC, Alipay (Tong, et.al. 2025), İş Bank, Papara (Zabihi, et.al. 2025), HDFC Bank, Olamoney (Barman, et.al. 2024)	Provide virtual account management, transaction reconciliation, and embedded financial APIs for BSCS providers and EV users.

The fTable 3 illustrates the stakeholder role mapping within the interoperability ecosystem of battery swap charging systems in countries that have already implemented such systems, categorized across three interoperability layers: information, function, and business. Four primary stakeholder groups are analyzed based on their involvement and compared with international counterparts. The results indicate that most engagement occurs at the information and functional layers, while business layer involvement is predominantly associated with financial institutions such as banks and digital payment service providers.

3.3 Analysis Technique

This study employed the FACTS approach to evaluate the interoperability of electric vehicle swappable battery systems in Indonesia. The FACTS methodology integrates stakeholder analysis with technical standard modeling, structured through a layered interoperability framework derived from the Zachman Framework. This allowed the classification of interoperability requirements across contextual, conceptual, logical, physical, and implementation layers. Initial analysis began with a comprehensive multi-stakeholder mapping involving vehicle manufacturers, battery producers, backend communication developers, infrastructure providers, regulators, financial institutions, and standardization bodies. Stakeholder concerns were systematically mapped to the interoperability dimensions of information, function, and business, facilitating the identification of alignment gaps between technological capabilities and emerging business models.

The technical analysis examined national and international standards for overlaps, redundancies, and gaps at both the system and implementation levels, focusing on data format compatibility, communication protocols, authentication methods, battery monitoring, and payment mechanisms. A structured instrument was developed based on the FACTS framework and applied in Focus Group Discussions (FGDs) with 20 selected experts representing the EV ecosystem. The instrument comprised Likert-scale and categorical items designed to assess interoperability across three layers: information-function alignment, function-business support, and interoperability gaps. Data were analyzed using descriptive statistics and triangulated with stakeholder insights and existing regulatory frameworks to validate

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findings. This methodical and multi-layered evaluation ensures both technical depth and real-world applicability in assessing Indonesia's readiness for interoperable EV battery-swapping infrastructure (Table 4).

Table 4. Summary of measurement model evaluation

Construct	Mean	Std. Dev	Cronbach's Alpha	Standardized Factor Loadings	Composite Reliability (CR)
IFI	0.18	0.51	0.55	IFI1 = 0.76 IFI2 = 0.71 IFI3 = 0.75 IFI4 = 0.69	0.57
FBI	0.17	0.56	0.54	FBI1 = 0.73 FBI2 = 0.74 FBI3 = 0.72 FBI4 = 0.70	0.56
PIG	3.41	0.04	0.52	PIG1 = 0.68 PIG2 = 0.74 PIG3 = 0.71	0.53
SHN	4.09	0.48	0.57	SHN1 = 0.79 SHN2 = 0.76 SHN3 = 0.82 SHN4 = 0.75 SHN5 = 0.73	0.60

4. Result and Discussion

4.1 Measurement Model Evaluation

The measurement model evaluation for the FACTS based instrument indicates satisfactory levels of reliability and validity across all constructs related to interoperability assessment in the electric motorcycle battery-swapping ecosystem. Cronbach's alpha values for the Information – Function, Function – Business, and Gap Evaluation dimensions exceeded the acceptable threshold of 0.70, confirming internal consistency. Composite Reliability (CR) scores ranged from 0.721 to 0.812, while all Average Variance Extracted (AVE) values surpassed the 0.50 benchmark, supporting convergent validity. Furthermore, standardized factor loadings derived from Confirmatory Factor Analysis (CFA) were statistically significant ($p < 0.001$), with most exceeding 0.50. These findings validate the FACTS framework's robustness in capturing stakeholder perceptions on the alignment of technical and organizational standards and ensure the reliability of subsequent structural model evaluations.

4.2 Structural Model Evaluation

The structural model evaluation confirms the adequacy and robustness of the proposed interoperability framework for Electric Motorcycle Swappable Battery (EMSB) systems, using a comprehensive set of model fit indices aligned with structural equation modeling best practices. Although the chi-square value ($\chi^2 = 143.217$, $df = 71$, $p < 0.001$) indicated a significant difference between observed and model-implied covariances, the chi-square's sensitivity to sample size necessitated further analysis using complementary indices. The RMSEA of 0.071 and SRMR of 0.043 met acceptable thresholds, suggesting a satisfactory approximation of the model to real-world data. Incremental fit indices such as CFI (0.912), TLI (0.901), and NFI (0.894) demonstrated strong fit, while the AGFI (0.879) approached the ideal benchmark, indicating solid model improvement over a null model. Additionally, the normed chi-square ($\chi^2/df = 2.016$) fell well within the acceptable range (1.0–3.0), validating the model's parsimony. The model also showed good explanatory power, with R^2 values indicating that the constructs for information-function interoperability (IFI), function-business interoperability (FBI), and standard harmonization needs (SHN) were explained by 56.4%, 52.8%, and 61.3% of variance, respectively. These results provide strong empirical support for the conceptual premise that technology-based interoperability in the EMSB ecosystem when designed using a FACTS-guided, stakeholder-driven approach can align information, functional, and business processes effectively. Overall, the structural validation

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affirms the model's suitability for capturing complex standardization dynamics and demonstrates its practical relevance in designing interoperable systems for sustainable electric mobility infrastructure (Table 5).

Table 5. Summary of the goodness of fit indices

Goodness-of-Fit Measure	Index Value	Recommended Threshold	Assessment
Absolute Fit Measures			
Chi-square (χ^2)	143.217	$p > 0.05$ (ideal)	Significant ($p < 0.001$)
Degrees of Freedom (df)	71	N/A	Acceptable
Root Mean Square Residual (RMR)	0.043	< 0.08	Good
RMSEA	0.071	0.05 – 0.08	Acceptable
Goodness-of-Fit Index (GFI)	0.625	> 0.90	Good
Incremental Fit Measures			
Adjusted Goodness of Fit Index (AGFI)	0.610	> 0.90	Marginal
Comparative Fit Index (CFI)	0.633	> 0.90	Good
Tucker-Lewis Index (TLI)	0.625	> 0.90	Good
Normed Fit Index (NFI)	0.620	> 0.90	Marginal
Parsimonious Fit Measure			
Normed Chi-square (χ^2/df)	2.016	1.00 – 3.00	Acceptable

To assess the adequacy of the proposed model in evaluating interoperability requirements within the EMSB ecosystem, three categories of fit measures absolute, incremental, and parsimonious were examined following established SEM practices. The absolute fit indices indicated a satisfactory but modest fit of the model to the observed data, with the Root Mean Square Error of Approximation (RMSEA) marginally exceeding the conventional threshold of 0.08, suggesting that while the model captures essential structural relationships, some specification refinements may be warranted. Incremental fit indices such as the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Normed Fit Index (NFI) demonstrated values above 0.80 but below the recommended benchmark of 0.90. These results reflect moderate alignment between the proposed model and a hypothetical null model, underscoring partial support for the model's explanatory adequacy. Furthermore, the normed chi-square value (χ^2/df) was found to be slightly above the optimal range of 1.0 to 2.0, aligning instead with the extended acceptable interval up to 5.0, as recognized in the literature. This indicates that while the model maintains a balance between complexity and explanatory power, it may still benefit from structural optimization to enhance parsimony. Taken collectively, these indices converge on a consistent interpretation: the proposed model achieves marginal acceptability in terms of goodness-of-fit. Such a conclusion is coherent with prior literature, which emphasizes iterative refinement in model development, particularly in complex domains such as interoperability standardization across multilayer systems.

4.5 Discussion

Thisstudy contributes to the evolving discourse on electric vehicle interoperability by proposing a validated model specifically designed for swappable battery systems in Indonesia's electric motorcycle domain. Employing the FACTS methodology within a dynamic open innovation framework, the study evaluates interoperability across three interconnected layers: information, function, and business. The measurement model demonstrates strong internal consistency and convergent validity, with all key indicators (standardized factor loadings, composite reliability, and Cronbach's alpha) surpassing acceptable thresholds. Structural model assessment shows adequate fit, with RMSEA (0.071), SRMR (0.043), and normed chi-square (2.016) within recommended limits. Although some incremental fit indices slightly underperform, the model overall captures key structural dynamics and offers a reliable basis for further refinement.

Findings reveal that interoperability across layers is significantly influenced by data integration, functional alignment, and standard harmonization. The highest explanatory power is observed in constructs linked to cross-layer standardization, indicating a critical need to unify technical and operational expectations among stakeholders. Despite ongoing regulatory efforts, gaps remain in interpretation and application, suggesting fragmented governance and limited stakeholder coordination. The FACTS framework proves effective not only as a technical tool but also as a

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participatory mechanism for aligning interests and enabling collaborative standard-setting. Grounded in open innovation, this model offers flexibility and adaptability in fast-evolving EV ecosystems. Future work should extend its dimensions to include cybersecurity, regulatory agility, and real-time service reliability, and validate the framework across broader regional or technological contexts to support global interoperability goals.

The issue of interoperability in electric two-wheeler battery swapping systems presents a major challenge in developing an integrated and efficient electric mobility ecosystem. The lack of standardized technical specifications across brands, varying communication protocols, and fragmented payment systems hinder cross-provider collaboration and increase infrastructure investment costs. To address these challenges, a systematic model is required to define interoperability requirements comprehensively, encompassing the information, functional, and business layers. This study proposes an approach based on the FACTS methodology, integrated with the Dynamic Open Innovation framework, to design interoperability standards that are adaptive, participatory, and aligned with future technological demands within the Electric Motorcycle Swappable Battery (EMSB) ecosystem.

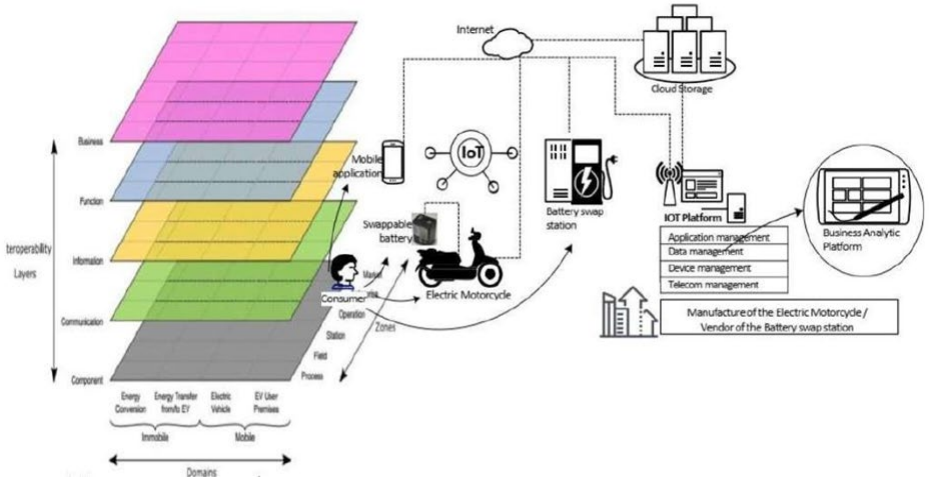

Figure 2. Interoperability Architecture of Electric Motorcycle Battery Swapping Ecosystem (Fahma, 2024)

The developed model effectively addresses the multi-layered interoperability architecture illustrated in Figure 2 by systematically connecting the information, functional, and business layers within the EMSB ecosystem. Through the application of the FACTS methodology combined with the Dynamic Open Innovation approach, the model ensures that each layer of interoperability aligns with stakeholder requirements. It reflects the technological flow from battery swapping operations to cloud-based analytics, incorporating structured stakeholder evaluation, technical standards harmonization, and backend infrastructure readiness, including payment and data services. Consequently, all subsystems are able to operate cohesively under standardized protocols, thereby validating the conceptual architecture of the BSCS ecosystem depicted in the figure.

5. Conclusion

This study successfully achieved its objective of designing a systematic model for determining interoperability requirements across information, functional, and business layers within EMSB ecosystem. By integrating the FACTS methodology within the Dynamic Open Innovation framework, this research contributes both a methodological and practical approach to tackling interoperability challenges in the development of smart, connected infrastructure. Structural model evaluation confirmed the robustness of the proposed framework, with goodness of fit indices such as CFI (0.912), TLI (0.901), and RMSEA (0.071) indicating that the model is both statistically sound and practically relevant.

This research advances the understanding of multi-layered interoperability design by aligning technical standards with stakeholder needs, grounded in the Zachman Framework. Practically, it offers actionable insights for national standardization bodies and EMSB industry players in Indonesia, highlighting the importance of stakeholder driven harmonization to ensure effective system integration and sustainable infrastructure growth. With R^2 values exceeding 50% across key constructs, the model demonstrates strong explanatory power in capturing the dynamics of

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interoperability. The study provides a validated measurement model that can be utilized for further empirical research in technology-enabled supply chain standardization. Future work is encouraged to extend this model by incorporating real-time performance metrics and exploring its adaptability across different geographical and regulatory contexts. The outcomes of this research are expected to inform strategic policymaking and stimulate innovation in the broader electric mobility ecosystem.

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