

Article

A Survey-Informed Digital Competitiveness Framework for Emerging Battery Manufacturing Ecosystems: Evidence from Romanian Cross-Sectoral Industrial Firms

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Abstract

The article proposes an exploratory approach that combines literature-based analysis of digital transformation and competitiveness in battery manufacturing ecosystems with survey evidence collected from Romanian companies operating in technology-related sectors. The empirical approach described provides indirect ecosystem-level evidence from Romanian firms potentially relevant to future battery value chains, as full-fledged manufacturers only now entering the strategic horizon. The study is founded on the need for companies to achieve a consistent and committed transformation that goes beyond adopting and integrating various digital technologies, reaching aspects related to production facilities, human–machine integration, and smart governance approaches. The objective of the research is to study the mutual impacts between facilities and processes on one hand, and technology on the other hand, in achieving competitiveness and sustainability for battery manufacturing ecosystems. In this regard, the paper investigates organizational capabilities, workforce adaptability, and digital technology deployment as enabling factors for a successful digital transformation. The results point to an improvement potential that may contribute to the resilience of the emerging battery industry under challenging conditions, while preparing for sector expansion brought about by developing electromobility and renewable energy options. The framework developed customizes general digital transformation capabilities into battery-manufacturing-specific requirements such as traceability, circularity, regulatory readiness, user safety, and ecosystem interconnectivity.

Keywords: battery ecosystems; battery industry; digital transformation; competitiveness



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1. Introduction

The battery industry is increasingly becoming a vital component of the economic and development strategies of many countries. Although well developed in the automotive sector for a considerable time, its expansion from starting batteries to electric vehicle (EV) driving batteries, and the much-needed storage capacity required by the green transition to renewable energy and power consumption of AI data centers, is an ongoing phenomenon that is difficult to manage and predict [1]. This current work seeks to understand the specific characteristics of this industry and how they can evolve in relation to extrinsic and intrinsic factors that can affect the competitiveness of the sector.

The starting point of the study is represented by the European Commission's Communication C (2025) 8950 final from December 2025 entitled "Battery Booster Strategy" [2], which has been acknowledged in Romania, where the research was performed, recently through the Decision of the Romanian Senate no. 66/2026 from April 2026 regarding the "Strategy on boosting battery production" [3]. This is the current level of public policy in the country (besides national energy strategies that focus on batteries for BESS—battery energy storage systems), with other numerous initiatives announced in the past 5 years by the private sector that are expected to be completed in the near future. An interregional ecosystem, involving more countries in Central and Eastern Europe, is not yet developed, but could represent a future scenario.

The European Union (EU) battery manufacturing landscape is a complex one to navigate, but it ultimately aims for competitiveness that is properly regulated to ensure sustainability, transparency, compliance and inclusiveness, and it includes the EU Battery Regulation, the Critical Raw Materials Act, the Ecodesign for Sustainable Products Regulation and the emerging battery passport (so far in the form of the Digital Product Passport), which should also be part of the Catena-X automotive data space developed at the EU level based on the Gaia-X data ecosystem.

As it stands at the moment, Romania is not among the champions of battery manufacturing capacity development in Europe, which could reach 1.7 GWh by 2030 [4]. In the proposed approach, the changes involved by the application of these documents are related to a larger understanding of the digital transformation (DT) of the economic landscape in Northwestern Romania, an important industrial region, and the home of one of the three battery manufacturers in the country. The following research goals are being addressed in this context:

- Identify DT capabilities in potential Romanian battery ecosystem firms;
- Connect emerging ecosystem features to competitiveness requirements;
- Propose an exploratory framework requiring future battery plant validation.

2. Methods

The main thesis investigated is related to the need to develop a supporting ecosystem for the supply chains that the battery industry requires and that this can be achieved faster and more effectively by employing frameworks and instruments specific to digital transformation, supported also by a green approach.

The main steps followed for the present investigation include (Figure 1):

- The study of 2 evidence bases (literature on digitalization and competitiveness in the battery industry and localized cross-sectoral survey for a potential host ecosystem to act as tailoring base);
- The development of competitiveness constructs that must be achieved in the battery industry (company readiness, workforce adaptability, digital transformation impact);
- The establishment of a digital technology roadmap based on prioritization and future integration scenarios of Industry 5.0 technologies;
- The formalization of a Digital Competitiveness Framework for Battery Ecosystems (DCF-BE) that includes an implementation roadmap for specific managerial and technical approaches, a continuous improvement loop and an output- and outcome-measuring array.

For the purpose of this analysis, the competitiveness dimensions to be detailed for the DCF-BE have been established starting from the mentioned evidence base (Figure 2):

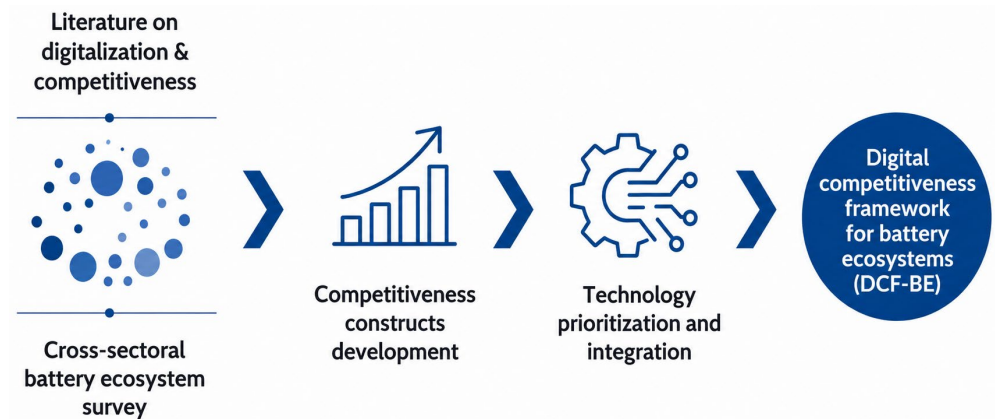


Figure 1. Research methodology and conceptual framework.



Figure 2. Dimensions of competitiveness for DCF-BE.

2.1. Survey Instrument and Statistical Analysis

The empirical component of the study is based on a structured survey applied to respondents from Romanian companies. The questionnaire captured company profile; digital transformation readiness; perceived organizational impact of digital transformation, knowledge, and use of digital technologies; learning needs; and employee adaptability in the context of digital transformation.

The questionnaire had 61 respondents, answering 33 questions utilizing the Likert scale. The questions in the questionnaire refer to the following:

- Company Profile;
- The company's level of readiness for DT;
- The perceived impact of DT;
- The level of knowledge and use of DT;
- The perception of employees looking at their job in the DT context.

The statistical analysis was conducted using IBM SPSS Statistics (Version 32.0). Descriptive statistics were used to characterize the sample and the main survey variables, while Cronbach's alpha was applied to assess the internal consistency of the main composite constructs: organizational readiness, perceived digital transformation impact, and workforce adaptability. Based on these reliability results, composite scores were computed as the mean of the validated items corresponding to each construct.

Pearson correlation analysis was then used to examine the relationships among organizational readiness, workforce adaptability, training support, and perceived digital transformation impact. A hierarchical linear regression model was also estimated to assess the extent to which organizational readiness, workforce adaptability and training support explain perceived digital transformation impact. The statistical analysis was complemented by a technology adoption gap assessment comparing the technologies known by respondents, the technologies actually used in their organizations and the technologies for which respondents expressed learning interest.

Although the survey was not limited exclusively to battery manufacturers, it targeted organizations operating within industrial and technological environments relevant for digital transformation and manufacturing competitiveness. The approach therefore supports the development of ecosystem-level insights applicable to the battery manufacturing sector.

2.2. Justification of the Ecosystem Approach

The empirical investigation presented in this article has been designed at the ecosystem level for the following considerations. Romanian industry is, at the present moment, establishing strategic priorities and developing capabilities to begin supporting a true battery manufacturing industry, with few players active, mostly from the automotive area where they have a long tradition. The competitiveness of this future industry cannot be achieved in an efficient manner without the proper foundations represented by raw materials and component suppliers, technology providers, engineering companies, IT firms, logistics operators, equipment manufacturers, universities, and research organizations, as well as other private and public actors that collectively enable digital transformation and innovation.

DT in the battery manufacturing sector requires capabilities that can be considered transversal across modern industrial sectors, including organizational readiness, workforce adaptability, and technology adoption, and are a prerequisite for the future companies that will contribute to this ecosystem. Consequently, the survey was conducted among Romanian firms that are active in economic fields and geographical regions that are expected to be involved in battery manufacturing outside of the automotive industry. The survey that informed the development of the current ecosystem approach included two main categories of companies: (1) battery component manufacturers (chemical processors, cell fabricators, electric and electronic component manufacturers, plastic and enclosure manufacturers, etc.), which represent the direct component actors; and (2) ecosystem-support actors (from the service, IT, and commerce sectors) that represent digital infrastructure, digital services, suppliers, logistics, distribution networks/retailers, and training capabilities needed by the envisioned battery value chains.

The empirical results presented can be considered ecosystem-level evidence supporting the conceptual development of the DCF-BE framework, while direct validation within battery manufacturing companies constitutes an area of future research, as these companies will begin to appear. This approach is aligned with the modern academic and policy consensus that industrial competitiveness materializes as an emergent behavior resulting from interconnected innovation ecosystems rather than from individual firms operating in isolation.

3. Literature Review

Digital transformation in the battery industry is heavily focused on the products themselves, as smart batteries and their charge/discharge and thermal management can significantly be improved using sensors and AI-powered software [5,6]. However, a significant improvement in potential for competitiveness stems from the digitalization

of the manufacturing companies and processes, compounded by similar approaches in the end-of-life part of the batteries' life-cycle [7]. This is even more important in the case of developing battery ecosystems, as they usually start working with mature technical solutions that can be acquired, but lack the expertise to use them for maximum benefits.

The most common approach employed for this purpose is related to Industry 4.0 and its associated instruments, technologies, and frameworks, which lead to smart manufacturing environments located within smart buildings. These include smart production facilities, ultra-responsive supply-chain and logistical operations, deployment of edge computing solutions, and automated manufacturing equipment such as machine tools, robots, electrochemical devices, etc. [8]. The hardware components must be heavily reinforced by the deployment of process AI, machine learning, machine vision and distributed computing solutions that enable real-time monitoring, predictive analytics and advanced process optimization [9]. Current trends include the development of complete factory digital twins and the moderation of the technological approach of Industry 4.0 with the human-centric philosophy of Industry 5.0 models [10].

The digital transformation of the battery sector is often discussed in conjunction with its green and sustainable transformation [11], which is a common occurrence for all industries, but more significant here due to the considerable environmental footprint of this domain. The decarbonization of the industry coupled with improving its water and resource consumption is mandatory to validate its contribution to the renewable energy and electrical vehicle booms. An important place in this transformation belongs to sustainable manufacturing technologies and practices together with circular economy implementation, which can be significantly potentiated by digitalization. At the same time, research is ongoing concerning new and environmentally friendly chemistries for energy storage [12,13], as well as advanced recycling technologies [14,15].

Digital technologies play a significant role in the evolution of manufacturing technologies, as well as fostering and enabling the use of advanced materials and electrochemical processes with low environmental impact. Similarly, when digital manufacturing processes are employed, the resulting changes in product quality and reliability and the optimization of scrap and non-conformities support better performance in battery applications and a more environmentally conscious production system [16]. Also, these approaches contribute to the development of innovation in the field leading to fully autonomous factories (a.k.a. "dark factories") and the foreseeable intersection of nanomanufacturing and quantum computing at a future time, affecting most industries [17].

These trends must be understood in the context of market and policy pressures that are present all over the world and are even more visible in the European Union, which has a strong commitment to the European Green Deal adopted in 2019, which requires an advanced battery industry to be successful [18]. The European Commission's push for developing the sector through the communication mentioned before, as well as its strategic orientation towards technological sovereignty and alleviating rare mineral dependence, has the potential to stimulate innovation and industrial scalability of advanced solutions for both battery products and manufacturing processes, leveraging the sustainable and responsible competitiveness of the domain [19,20]. Global competition with other economic players or blocks can be considered an important driving force that contributes to a fast-paced development in the field.

More importantly, it becomes apparent that the widespread impact of DT on almost all aspects of life and work must also be integrated in the evolving battery industry to secure its position as a vital sector of the European economy moving forward [21]. As AI and other instruments become more prevalent, the batteries that power cars, robots, smart devices, and electrical grids are expected to undergo this transformation to be able to upend the

competitiveness of other sectors through their own enhanced performance at a competitive price level [22,23].

Within this context, the current work looks at DT for the battery sector not only as a technological upgrade, but as a complex, detailed, and transformative competitiveness mechanism for battery ecosystems. Beyond its impact on productivity, costs and quality, this approach has the capability to influence key factors such as traceability, circularity, trend monitoring, and strategy deployment. For the emerging battery ecosystems, the main challenges reside in reducing the time needed for individual DT success, but also for interfacing technological and operational systems into a functional network that enable successful trade-offs among actors. For this purpose, it is considered necessary to develop a comprehensive methodology that can be applied by companies and the industry at the same time, in a fractal model.

By integrating DT principles into the advanced digital tools being implemented in many companies such as data infrastructure scaling, process monitoring, AI-based decision support, digital twin deployment, and circular economy tracking, the integration with sustainability performance indicators can be achieved more effectively and efficiently. As a consequence, the emerging battery ecosystems have a higher in-built chance of becoming healthy and prosperous, thus lending more resilience and more adaptability to the European economy they are part of.

4. Results

The empirical analysis is based on 61 valid responses collected from Romanian companies. The questionnaire included items related to company profile, digital transformation maturity, organizational readiness for digital transformation, perceived digital transformation impact, knowledge, and use of digital technologies, learning needs, and workforce adaptability. The survey results were processed using IBM SPSS Statistics. The analysis includes sample profiling, reliability analysis, composite score construction, correlation analysis, multiple regression, and a technology adoption gap assessment.

4.1. Sample Profile and Digital Transformation Maturity

The sample included 61 valid respondents from Romanian companies (see Table 1). The most represented sectors were services, production, commerce, and IT. Services accounted for 34.4% of the sample, production for 29.5%, commerce for 13.1% and IT for 11.5%. Almost half of the respondents worked in companies with more than 20 years of activity on the Romanian market. Regarding digital transformation maturity, most respondents indicated that their companies were already in the use stage, while smaller shares reported early design, implementation, or analysis stages.

Table 1. Sample profile and digital transformation maturity.

Industry/Sector	Proportion in Sample	General Level of Experience	General Level of DT
Production	29.5%	>20 years	Low to Medium
Services	34.4%	≈20 years	Medium
Commerce	13.1%	<20 years	Low to Medium
IT	11.5%	<20 years	High

4.2. Reliability of the Main Constructs

Reliability analysis was conducted for the three main constructs used in the empirical model: organizational readiness, perceived digital transformation impact, and workforce

adaptability (see Table 2). Organizational readiness was measured through five items capturing competitive positioning, financial readiness, logistical readiness, and staff qualification for digital transformation. Perceived digital transformation impact was measured through twelve items related to customer attractiveness, connectivity, communication, security, productivity, agility, product quality, efficiency, flexibility, supply-chain optimization, continuous learning opportunities, and overall improvements. Workforce adaptability was measured through five items related to communication, task completion, perceived safety in using digital technologies, creativity, and adaptation to organizational change.

Table 2. Reliability analysis of the main constructs.

Construct	Number of Items	Cronbach's Alpha	Interpretation
Organizational readiness	5	0.891	Excellent internal consistency
Perceived digital transformation impact	12	0.955	Excellent internal consistency
Workforce adaptability	5	0.841	Good internal consistency

All three constructs exceed the commonly accepted threshold of 0.70, supporting the use of composite scores in the subsequent analyses. The very high alpha obtained for perceived digital transformation impact indicates strong internal consistency, although it may also suggest conceptual proximity among several impact-related items.

Item-total correlation values ranged between 0.327 and 0.781. The highest correlations were recorded for task completion (0.781), confidence in using digital technologies (0.739), and expression of skills and creativity (0.733). Adaptation to organizational change also showed a strong contribution to the construct (0.686).

The communication-related item recorded the lowest item-total correlation (0.327), indicating a weaker association with the remaining variables. Additionally, the “Cronbach's alpha if item deleted” analysis showed that removing this item would increase the overall reliability coefficient from 0.841 to 0.886. However, the variable was retained due to its relevance for evaluating employee interaction within digitally transformed work environments.

4.3. Descriptive Statistics and Correlations

Composite scores were computed for organizational readiness, perceived digital transformation impact, and workforce adaptability (see Table 3). The descriptive results indicate that respondents perceive a moderate to positive level of organizational readiness and digital transformation impact, while workforce adaptability records the highest average score. This suggests that employees tend to evaluate their own capacity to adapt to digital transformation more positively than the overall organizational readiness of their companies.

Table 3. Descriptive statistics and correlations.

Variable	Mean	SD	1	2	3
1. Organizational readiness	3.47	0.82	1		
2. Perceived digital transformation impact	3.70	0.77	0.740 **	1	
3. Workforce adaptability	3.94	0.69	0.503 **	0.728 **	1

Note: N = 61. ** $p < 0.01$.

The correlation analysis shows positive and statistically significant relationships among the three constructs. Organizational readiness is strongly associated with perceived digital transformation impact ($r = 0.740$, $p < 0.001$), while workforce adaptability is also strongly associated with perceived digital transformation impact ($r = 0.728$, $p < 0.001$). A moderate positive relationship is observed between organizational readiness and workforce adaptability ($r = 0.503$, $p < 0.001$). These results indicate that perceived digital transformation impact is connected both to organizational preparedness and to the capacity of employees to adapt to digital change.

4.4. Predictors of Perceived Digital Transformation Impact

A multiple linear regression model was estimated in order to examine whether organizational readiness, workforce adaptability and training support predict perceived digital transformation impact (see Table 4). The dependent variable was the perceived digital transformation impact score, while the independent variables were organizational readiness, workforce adaptability and the extent to which employees receive training when new digital technologies are implemented.

Table 4. Multiple regression predicting perceived digital transformation impact.

Predictor	B	SE	β	t	p	95% CI for B	VIF
Constant	0.123	0.303	—	0.406	0.687	[−0.484, 0.731]	—
Organizational readiness	0.403	0.074	0.433	5.446	<0.001	[0.255, 0.551]	1.460
Workforce adaptability	0.369	0.100	0.334	3.703	<0.001	[0.169, 0.569]	1.878
Training support	0.196	0.067	0.268	2.941	0.005	[0.062, 0.329]	1.916

Model summary: $R = 0.868$; $R^2 = 0.753$; adjusted $R^2 = 0.740$; $F(3, 57) = 58.037$; $p < 0.001$; Durbin–Watson = 2.232.

The regression model was statistically significant, $F(3, 57) = 58.037$, $p < 0.001$, and explained 75.3% of the variance in perceived digital transformation impact ($R = 0.868$; $R^2 = 0.753$; adjusted $R^2 = 0.740$). The Durbin–Watson value was 2.232, indicating no major autocorrelation problem in the residuals. The variance inflation factor values ranged from 1.460 to 1.916, which indicates that multicollinearity was not problematic.

The results show that all three predictors are statistically significant. Organizational readiness is the strongest predictor of perceived digital transformation impact ($\beta = 0.433$, $p < 0.001$), followed by workforce adaptability ($\beta = 0.334$, $p < 0.001$) and training support ($\beta = 0.268$, $p = 0.005$). These findings suggest that the perceived impact of digital transformation does not depend only on the existence or use of digital technologies. It is also associated with the preparedness of the organization, the ability of employees to adapt to digital change and the presence of training mechanisms when new technologies are implemented.

For the Digital Competitiveness Framework for Battery Ecosystems, these results are relevant because they indicate that technology adoption should not be treated as an isolated technical process. Digital competitiveness requires an integrated approach in which organizational readiness, workforce adaptability and continuous training support the effective implementation of advanced digital technologies.

From a managerial perspective, the regression results suggest that digital transformation impact should be approached as the outcome of an integrated capability system. Organizational readiness provides a structural and strategic basis, workforce adaptability

supports the human and operational absorption of digital change, and training support facilitates the transition from technology introduction to effective use.

4.5. Comparison by Digital Transformation Maturity Stage

An additional exploratory analysis compared respondents from companies situated in early or developing stages of digital transformation with respondents from companies situated in more advanced or operational stages (see Table 5). Companies in the early/developing category included organizations situated in the early, design or implementation phases of digital transformation, while the advanced/operational category included companies situated in the use or analysis phases.

Table 5. Comparison by digital transformation maturity stage.

Variable	Early/Developing Mean Rank	Advanced/Operational Mean Rank	Mann–Whitney U	Z	p
Organizational readiness	18.65	37.02	163.000	−3.812	<0.001
Perceived DT impact	22.43	35.18	238.500	−2.644	0.008
Employee adaptability	24.60	34.12	282.000	−1.982	0.047
Training support	25.68	33.60	303.500	−1.714	0.087

Because of the relatively small sample size and the non-normal distribution of some variables, the Mann–Whitney U test was used to compare the two groups.

The results indicate that respondents from more digitally advanced companies report significantly higher levels of organizational readiness and perceived digital transformation impact. Workforce adaptability also records significantly higher values among respondents from advanced/operational companies, although the difference is smaller. Training support tends to be higher in more advanced organizations, but the difference does not reach conventional levels of statistical significance.

Effect sizes were also calculated using $r = |Z|/\sqrt{N}$. The effect size was moderate for organizational readiness ($r = 0.49$), small-to-moderate for perceived digital transformation impact ($r = 0.34$), small-to-moderate for workforce adaptability ($r = 0.25$), and small for training support ($r = 0.22$).

The strongest difference between the two groups is observed for organizational readiness, suggesting that companies situated in more advanced stages of digital transformation perceive themselves as significantly better prepared from a financial, logistical and workforce perspective. A similar pattern is observed for perceived digital transformation impact, indicating that companies with higher digital maturity tend to perceive stronger organizational benefits associated with digital transformation.

Although workforce adaptability is also significantly higher in advanced/operational organizations, the difference is comparatively smaller, which may indicate that employee adaptability develops progressively alongside organizational digital maturity. Training support shows a positive tendency in more advanced organizations, but the difference is not statistically significant at the 0.05 level.

4.6. Digital Technology Awareness, Use and Learning Needs

In addition to the construct-based analysis, the survey examined the digital technologies known by respondents, the technologies currently used in their organizations and the technologies respondents would like to learn in the future. This comparison provides useful

insights regarding the gap between technological awareness, practical implementation, and future capability-building needs within industrial organizations.

Multiple choices were allowed for this question, and each respondent selected around three technologies on average (Table 6).

Table 6. Digital technology awareness, use, and learning needs.

Technology	Known	Used	Want to Learn
Artificial intelligence	45	32	24
Cloud computing	36	28	16
Cybersecurity	34	25	17
3D design	31	23	16
Sensors	28	20	10
Robots	24	16	15
Industrial internet of things	19	13	19
Blockchain	17	6	18
Virtual reality	20	7	15
Big data	13	10	14
Digital twins	10	4	7
Augmented reality	15	1	8

The results indicate that mature and widely diffused technologies, such as artificial intelligence, cloud computing and cybersecurity, tend to record higher levels of both awareness and practical use. In contrast, technologies such as digital twins, augmented reality, virtual reality, blockchain and Industrial Internet of Things display larger gaps between technological awareness and actual implementation.

Artificial intelligence leads the ranking with 53.3%, used by more than half of the respondents. Cloud computing (46.7%) and cybersecurity (41.7%) follow closely, indicating a solid base of storage, collaboration, and risk-management tools. A second tier groups 3D Design (38.3%), sensors (33.3%), and robots (26.7%), all of which fit the industrial profile of the surveyed companies. The remaining technologies are clearly less common: IoT (21.7%), Big Data (16.7%), VR (11.7%), blockchain (10.0%), digital twin (6.7%) and AR (1.7%).

These findings suggest that the main challenge is not only the awareness of advanced digital technologies, but also the organizational capability to implement and integrate such technologies into operational processes. At the same time, the relatively high learning interest associated with several advanced technologies indicates the existence of future demand for digital skill development and applied training initiatives.

The highest learning demand was recorded for AI (40.0%), followed by IoT (31.7%), blockchain (30.0%) and cybersecurity (28.3%). Moderate levels of interest were observed for 3D Design (26.7%), cloud technologies (26.7%), VR (25.0%), robots (25.0%), and Big Data (23.3%). Lower levels of learning interest were associated with sensors (16.7%), AR (13.3%), and digital twin technologies (11.7%).

Based on the overall structure of the answers collected, and factoring in local, in-the-field expertise, we interpret the results to mean that cost, skills, data infrastructure, system interoperability, cybersecurity, return on investment uncertainty and limited battery-specific compliance pressure may explain the gaps detected by the survey. However, the questionnaire did not include this specific topic, so this reasoning is speculative.

4.7. Implications for the Digital Competitiveness Framework for Battery Ecosystems

The empirical findings support the proposed Digital Competitiveness Framework for Battery Ecosystems by highlighting several organizational and ecosystem-level conditions associated with successful digital transformation.

The regression analysis indicates that organizational readiness, workforce adaptability, and training support are significant predictors of perceived digital transformation impact. This result suggests that digital competitiveness depends not only on the acquisition of digital technologies, but also on the preparedness of organizations and employees to integrate these technologies effectively.

The comparison between early/developing and advanced/operational organizations further supports this interpretation. More digitally mature organizations report higher readiness, stronger perceived impact, and greater workforce adaptability, which suggests that digital maturity should be understood as a cumulative organizational capability rather than as a purely technical implementation stage.

The technology adoption gap analysis adds an ecosystem-level perspective. Awareness of advanced technologies is often higher than actual implementation, especially for digital twins, blockchain, augmented reality and Industrial Internet of Things. This is particularly relevant for the battery manufacturing ecosystem, where digital integration is increasingly connected to competitiveness, traceability, process optimization, and supply-chain resilience.

These findings suggest that a competitive digital ecosystem for battery manufacturers requires more than technological investment. It also requires workforce development, organizational readiness, applied training mechanisms, collaborative innovation environments, and technology transfer support structures.

4.8. Operationalization of the DCF-BE for Battery Manufacturing Ecosystems

The proposed framework is designed as a conceptual tool that supports public and private efforts to rapidly develop battery manufacturing ecosystems within EU countries, with Romania serving as a possible testing ground. In order to facilitate its transition into economic and social reality, an operationalization approach is proposed below, connecting DT, the battery sector and industrial competitiveness (Table 7).

Table 7. Operationalization scheme for the DCF-BE model.

DCF-BE Addressability	Generic Digital Transformation Capability	Battery-Sector-Specific Requirements	Competitiveness Enablers
Data infrastructure	Interoperable data systems, ERP/MES/PLM integration; cloud/edge data flows.	Battery (product) digital passport data, material traceability, cell/batch traceability, supplier data exchange, lifecycle data.	Supporting compliance, simplifying recalls, warranty analysis, and circularity documentation.
Process digitalization	Sensors, IoT, AI analytics, digital twins, machine vision.	Electrode coating monitoring, cell assembly monitoring, formation analytics, defect prediction, process variability control.	Improves yield, reduces scrap, improves quality, enhances stability, and accelerates process maturity.
Quality and safety	Automated inspection, risk analytics, real-time monitoring.	Thermal-risk indicators, material contamination control, safety-critical tasks, process deviations, and cell reliability indicators.	Reducing in-use failures, diminishing cost-of-risk alleviation, safety incidents management, and warranty exposure.

Table 7. *Cont.*

DCF-BE Addressability	Generic Digital Transformation Capability	Battery-Sector-Specific Requirements	Competitiveness Enablers
Facilities and utilities	Smart building, energy management, environmental monitoring.	Clean-room control, humidity control, energy/water use monitoring, compressed air optimization.	Battery production becomes less resource-intensive; facility control directly affects costs, quality and sustainability, and the bottom line.
Workforce and training	Digital skills, adaptability, continuous learning.	Operator training for electrochemical process tuning, traceability routines, safety protocols, digital quality management systems.	Transforms technology acquisition into reliable operational use contributions to the manufacturing system.
Supply chain and networks	Digital supplier coordination, logistics interconnections, collaborative platforms.	Critical raw material traceability, supplier qualification, data exchange, recycling and circularity information loops.	Enables resilience and emergency relief, regulatory readiness, and value-chain integration.
Sustainability and circularity	Environmental data tracking, circular economy indicators, decarbonization indicators.	Carbon footprint data, recycled content tracking, second-life and additional-lives status, recycling management data.	Connects digitalization to EU sustainability and circularity expectations, ensures access to funding, and improves image.

Creating the proper conditions for achieving these targets through economic policies and regulations, as well as market mechanisms, has the potential to lead to successful battery manufacturing ecosystems that are based on the mentioned competitive advantages in various combinations for various actors.

5. Discussion

The present study provides exploratory empirical support for selected organizational assumptions of the proposed Digital Competitiveness Framework for Battery Ecosystems (DCF-BE). The findings do not provide direct validation in battery manufacturing plants, but they indicate that digital competitiveness cannot be understood exclusively through the lens of technological acquisition or automation investments. Instead, the results suggest that organizational readiness, workforce adaptability, and training support represent inter-connected capability domains that influence the perceived impact of digital transformation for emerging battery manufacturing ecosystems.

The findings also support the transition from technology-centered Industry 4.0 approaches toward more human-centric Industry 5.0 perspectives. The significant role of workforce adaptability and training support suggests that industrial competitiveness increasingly depends on the interaction between technological capabilities and human organizational capacities.

The regression model used in this paper is based on association and, thus, is exploratory in nature. The cross-sectional self-reported data collected from the companies is not an indicator of causality, and significant differences are possible. The regression analysis demonstrates that organizational readiness is the strongest predictor of perceived digital transformation impact. This finding is consistent with previous research emphasizing that

successful digital transformation depends not only on technological infrastructure, but also on organizational capabilities, managerial preparedness, and the strategic alignment of internal resources. Organizations that perceive themselves as financially, logistically, and operationally prepared for digital transformation also tend to perceive stronger benefits associated with digital technologies. In the context of battery manufacturing, this result is particularly important because the sector is characterized by high technological complexity, strict quality requirements, rapidly evolving supply chains and increasing sustainability pressures.

The results also highlight the important role of workforce adaptability in supporting digital transformation outcomes. Employees who perceive themselves as capable of communicating, adapting, and performing tasks in digitally transformed environments also report higher perceived digital transformation impact. This result supports the human-centric perspective associated with Industry 5.0 approaches, according to which technological transformation should not be treated as a purely technical process, but rather as an organizational and social transition involving continuous learning, collaboration, and adaptation.

Training support emerged as a significant predictor in the regression model, suggesting that organizations which provide training during the implementation of new digital technologies are more likely to perceive positive digital transformation outcomes. Although the comparison between maturity groups did not reveal statistically significant differences for training support at the conventional 0.05 threshold, the positive tendency observed among digitally advanced organizations indicates that workforce development remains an important enabling condition for digital competitiveness. In practice, even organizations situated in earlier stages of digital transformation may benefit substantially from targeted training programs and workforce development initiatives.

The comparison between organizations situated in early/developing and advanced/operational stages of digital transformation provides additional support for the proposed framework. Companies characterized by more advanced digital maturity reported significantly higher organizational readiness and perceived digital transformation impact. These findings support the idea that digital transformation maturity represents a cumulative organizational capability that develops progressively through managerial learning, operational integration, and technological experience. The moderate-to-large effect size observed for organizational readiness further strengthens this interpretation and suggests that digital maturity is meaningfully associated with organizational preparedness.

Another important contribution of the study concerns the technology adoption gap analysis. The results reveal visible differences between technological awareness and practical implementation for several advanced technologies, including digital twins, blockchain, virtual reality, augmented reality, and Industrial Internet of Things solutions. While respondents demonstrate moderate or high levels of awareness and learning interest regarding these technologies, actual implementation levels remain comparatively limited. This finding suggests that technological diffusion within industrial ecosystems is constrained not only by knowledge availability, but also by implementation capacity, investment requirements, integration complexity, and workforce readiness.

From the perspective of the battery manufacturing ecosystem, the adoption gap identified for advanced technologies is highly relevant. Technologies such as digital twins, Industrial Internet of Things, AI-supported analytics, and blockchain-based traceability systems are increasingly associated with process optimization, predictive maintenance, quality assurance, supply-chain transparency, and sustainability monitoring in battery production environments. Consequently, organizations that fail to progress from technological awareness to operational implementation may encounter increasing competitive disadvantages as industrial ecosystems become more digitally integrated and sustainability-oriented.

These observations may have multiple complex causes: high investment costs, digital skills scarcity, insufficient data infrastructure, uncertainty regarding return on investment, interoperability issues, cybersecurity concerns, and limited knowledge about battery-specific regulatory requirements such as traceability and battery passport data. The survey did not measure such causes, and their influence should be interpreted as possible explanatory mechanisms, not validated facts, while at the same time they will constitute priorities for future empirical validation.

The study also supports the idea that digital competitiveness in battery manufacturing should be approached at the ecosystem level rather than only the individual company level. The empirical results suggest that competitiveness depends simultaneously on organizational readiness, workforce capabilities, technological diffusion, and learning infrastructure. This implies that universities, vocational training centers, technology transfer organizations, innovation hubs, and public policy actors may all play important roles in facilitating digital transformation and industrial modernization. The development of collaborative innovation environments and ecosystem-based support structures may therefore become increasingly important for accelerating the digital transition of industrial sectors connected to battery manufacturing and electromobility.

5.1. Managerial Implications

The results suggest that managers involved in industrial digital transformation initiatives should avoid treating digital competitiveness exclusively as a technological investment process. Organizational readiness, workforce adaptability, and training support represent interconnected managerial priorities that significantly influence the perceived impact of digital transformation.

From a practical perspective, organizations should prioritize the development of internal readiness capabilities before large-scale technology deployment. This includes managerial alignment, workforce preparation, operational flexibility, and the creation of continuous learning mechanisms. In parallel, the technology adoption gap analysis suggests that organizations may benefit from phased implementation approaches in which awareness-building, pilot experimentation and targeted employee training precede full operational integration of advanced technologies such as digital twins, Industrial Internet of Things or blockchain systems.

These implications can only be observed in the real battery manufacturing environment and for this future validation in the sector, a table of relevant key process indicators (KPIs) to track and monitor in connection with the DCF-BE is proposed below (Table 8).

Table 8. Framework validation approach and indicators.

Survey Construct/ DCF-BE Component	Battery Ecosystem Interpretation	Objective KPIs Proposed for Future Validation in the Battery Manufacturing Sector
Organizational readiness	Capacity to integrate digital and regulatory transformations.	Digital maturity indicators, digital audit results, investment amounts, MES/ERP/PLM integration level, OEE, time to deploy new digital modules.
Workforce adaptability	Capacity of employees to work in digitally supported battery operations.	Training completion rate, certification achievement, employee error rate, changeover performance, adoption rate of digital operational tools.

Table 8. *Cont.*

Survey Construct/ DCF-BE Component	Battery Ecosystem Interpretation	Objective KPIs Proposed for Future Validation in the Battery Manufacturing Sector
Training support	Mechanism to convert technology acquisition into effective operational use.	Training hours per employee, onboarding time, competency assessment results, pre- vs. post-training comparison.
Technology adoption	Operational digitalization complexity and maturity.	Sensor coverage, IoT-connected assets, digital twin deployment level, machine vision inspection coverage, automated data refresh rate.
Quality and process control	Digital support for controlled battery manufacturing processes.	Process yield, scrap rate, defect detection rate, rework rate, process capability, warranty claim rate.
Traceability and compliance readiness	Ability to document and process material, process and lifecycle data.	Battery passport coverage, traceability level by batch/cell, supplier data coverage, regulatory requirement coverage, critical raw material documentation.
Sustainability monitoring	Ability to measure and improve environmental performance and indicators.	Energy use per cell/kWh, water use, carbon footprint data, recycled content data, and second-life and multiple-life data.

For organizations operating within industrial ecosystems connected to battery manufacturing, digital competitiveness may increasingly depend on the ability to combine technological modernization with organizational adaptability and collaborative ecosystem development.

5.2. Limitations and Future Research Directions

The study has several limitations that should be considered when interpreting the results. The empirical analysis is based on 61 respondents, which provides useful exploratory evidence but limits the generalizability of the findings. In addition, the survey was conducted in Romania and therefore reflects a specific regional and industrial context. The sample also included organizations from a broader industrial ecosystem relevant to battery manufacturing, rather than battery manufacturers exclusively. For this reason, the findings should be interpreted as ecosystem-level evidence, not as direct evidence from battery producers only. The cross-sectional design of the study also limits the possibility of drawing causal conclusions regarding the long-term development of digital transformation capabilities.

Future research could strengthen and extend the proposed framework by using larger and more specialized samples focused directly on battery manufacturers and related supply-chain actors. Longitudinal studies would also be useful for examining how organizational readiness, workforce adaptability, training support, and technology adoption evolve across different stages of digital transformation maturity. Comparative studies across European industrial ecosystems could further clarify how institutional conditions, technological capabilities and workforce-related factors shape the competitiveness of battery manufacturing in the context of green and digital transitions.

6. Conclusions

The present study provides ecosystem-level empirical evidence supporting selected assumptions of the proposed framework—the Digital Competitiveness Framework for Battery Ecosystems (DCF-BE)—by integrating organizational readiness, workforce adaptability, training support, and digital technology adoption perspectives within a broader industrial ecosystem relevant to battery manufacturing. The research combined literature analysis with an empirical survey conducted among Romanian companies in order to examine the organizational and technological conditions associated with digital transformation and industrial competitiveness [24].

The findings indicate that organizational readiness, workforce adaptability, and training support are significant predictors of perceived digital transformation impact. Organizational readiness emerged as the strongest predictor, suggesting that digital competitiveness depends not only on technological investments, but also on the strategic, operational, and human capabilities required to support digital transformation processes effectively. In addition, organizations situated in more advanced stages of digital transformation reported significantly higher levels of readiness, perceived impact and workforce adaptability compared to organizations in earlier stages of digital maturity [25,26].

The study also identified visible gaps between awareness and practical implementation for several advanced digital technologies, including digital twins, blockchain, augmented reality and Industrial Internet of Things solutions. These findings suggest that industrial competitiveness increasingly depends on the capacity of organizations to transform technological awareness into operational integration supported by workforce development and organizational learning mechanisms.

From the perspective of the battery manufacturing ecosystem, the results emphasize that digital competitiveness should be approached as a multidimensional organizational capability-building process rather than exclusively as a technological modernization initiative. The proposed framework therefore highlights the importance of combining technological investments with managerial preparedness, workforce adaptability, continuous training, and ecosystem-level collaboration in order to support the digital and sustainable transformation of industrial environments connected to battery manufacturing and electromobility.

Several limitations should nevertheless be acknowledged. The study is based on a relatively small sample of Romanian companies and does not focus exclusively on battery manufacturers. In addition, the cross-sectional design limits the possibility of drawing causal conclusions regarding the long-term evolution of digital transformation capabilities. Future research may therefore extend the proposed framework through larger and more specialized samples, longitudinal analyses and comparative investigations across European industrial ecosystems associated with battery manufacturing and green transition strategies.

An additional methodological limitation is due to the self-reported questionnaire data collected. As a consequence, the identified relations may be partially influenced by common-method variance and subjective perceptions of the respondents, rather than objectively reflecting organizational performance changes.

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