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## SUBSTANTIATION OF A SYNERGETIC QUALITY MANAGEMENT MODEL FOR NEW ENERGY VEHICLES WITHIN THE TQM, LEAN, AND SIX SIGMA PARADIGMS

He Ke, Chorna O.Y.

## ОБҐРУНТУВАННЯ СИНЕРГЕТИЧНОЇ МОДЕЛІ УПРАВЛІННЯ ЯКІСТЮ НОВИХ ЕНЕРГЕТИЧНИХ ТРАНСПОРТНИХ ЗАСОБІВ У ПАРАДИГМІ КОНЦЕПЦІЙ TQM, LEAN ТА SIX SIGMA

Хе Ке, Чорна О.Ю.

*The article provides a comprehensive theoretical and applied substantiation of a synergetic quality management model for new energy vehicles (NEVs) in the context of rapid technological transformation and intensifying global competition. A paradigm shift is substantiated, moving from traditional reactive end-of-process inspection to a proactive whole-life-cycle management model based on the "Quality by Design" concept. It is proven that in conditions of high technological complexity of intelligent electric transport systems, isolated inspection methods lose their effectiveness, giving way to an integrated "design-manufacturing-service" system. The scientific novelty of the research lies in the conceptualization of an integrated toolkit that combines the philosophy of Total Quality Management (TQM), Lean Production tools, and Six Sigma precision. Two strategic stages of transformation are detailed: at the development stage: the implementation of structured processes (IPD) and preventive modeling tools (DFMEA, CAE), which ensure the elimination of up to 70% of potential defects before the start of mass production. In the manufacturing cycle: a transition to precision management through error-proofing systems, automated intelligent inspection, and end-to-end component traceability based on RFID/QR technologies. Particular attention is paid to the institutional and cultural determinants of the management system's stability. The role of cross-functional collaboration and management leadership is substantiated as a "soft" infrastructure that ensures the removal of information barriers and the formation of a "quality-first" culture. Based on a comparative analysis of traditional and innovative management models, it is proven that digital transformation and the use of Big*

*Data are the only viable ways to achieve target reliability indicators in mass production scales.*

*The research results form a stable contour of municipal and industrial vitality for the industry, offering enterprises mechanisms for transitioning from a "scale expansion" strategy to a "high-tech competitiveness" strategy in the global market.*

**Keywords:** *new energy vehicles; quality management; TQM; Six Sigma; quality management system; digitalization; management leadership; preventive management; continuous improvement; design verification plan.*

**Problem statement.** Focusing on the key challenges in the development of the current new energy vehicle industry, this paper puts forward the core research question: against the backdrop of rapid industrial development, high technological complexity and growing consumer demands for quality and reliability, the traditional and isolated end-of-process quality inspection model can no longer adapt to the industry's demand for high-quality development. New energy vehicles are plagued by frequent quality pain points such as battery safety hazards, false range claims and intelligent system malfunctions, coupled with the profound transformation of market competition from "policy-driven" to "market-driven". Therefore, how to systematically construct and effectively implement a preventive and systematic quality management system covering the entire product life cycle of "development-manufacturing-service", so

as to ensure the high reliability, consistency and market competitiveness of products, and ultimately safeguard consumer safety and the healthy development of the industry, has become a strategic issue that new energy vehicle enterprises urgently need to address.

#### **Analysis of recent studies and publications**

The systematization of current research in the field of quality management for new energy vehicles (NEVs) for the period 2017–2025 demonstrates a profound transformation of methodological approaches toward ensuring the reliability of high-tech products. Modern scientific discourse, represented in the studies by Yao Pingli [9], Liu Wenxia [4], and Yu Ruiqiang [5], is focused on shifting the emphasis toward preventive management based on the "Design Quality Management" (DQM) concept. It has been proven that the strategic priority of defect prevention during the design stage, combined with precision control of manufacturing technological processes, is a fundamental determinant of the viability of electric transport systems.

Concurrently, the theoretical basis of the industry is evolving toward the synergetic integration of classical and innovative management paradigms. The theoretical foundations for the formation of quality management systems in Ukraine have been thoroughly investigated in the works of M. I. Shapoval and O. I. Momot [13, 14, 15]. In particular, the concept of integrating quality system elements, as proposed by O. I. Momot, serves as a basis for developing modern management models in the context of industrial digitalization. Within this framework, the scientific community substantiates the necessity of synthesizing the Total Quality Management (TQM) philosophy, Lean Production tools, and the Six Sigma methodology. This synergy enables a transition from a reactive "defect detection" model to a proactive system of process prevention and continuous improvement.

The technological aspect of the research, highlighted in the works of Yang Weijian [6], Hu Bixia [8], Chen Hao [10], and Sun Liangquan [11], emphasizes the implementation of Failure Mode and Effects Analysis (FMEA) and the digital transformation of control operations. The efficiency of automated inspection systems based on machine vision, laser measurements, and RFID identification is considered a key tool for ensuring end-to-end traceability and the rapid identification of root causes of defects. According to recent publications, the promising vector of development is the

utilization of Big Data, Artificial Intelligence, and Digital Twins for predictive quality analysis.

Alongside technical and technological solutions, the works of Zhang Yali and Zhao Manfu [7] emphasize the critical importance of institutional and socio-cultural factors, such as cross-functional collaboration, management leadership, and staff competency development, which form the organizational basis for the resilience of the management system. Thus, the covered body of literature, including both theoretical discussions and applied aspects of manufacturing precision, creates a holistic scientific basis for the development and substantiation of the whole-life-cycle quality management model for NEVs proposed in this paper.

**The purpose of the article** The aim of the article is to provide a theoretical substantiation and develop a holistic scientific and practical toolkit for a whole-life-cycle quality management system for New Energy Vehicles (NEVs) as a fundamental condition for ensuring their competitiveness in the context of global technological transformation.

The achievement of this aim involves the sequential resolution of a complex set of scientific objectives:

the first objective begins with the theoretical convergence of the key components of the quality management system and the determination of its strategic significance for the sustainable development of the electric vehicle industry;

the next stage of the research is the methodological substantiation of the implementation architecture, which entails an in-depth analysis of technological tools and quality management business processes during critical phases — from the stage of market planning and product development to the direct manufacturing cycle;

a significant place in the study is occupied by the identification of systemic quality assurance factors, which allows for the isolation and generalization of the role of "soft" management elements, specifically cross-functional collaboration, human capital potential, and the strategic leadership of top management;

the final vector of the research is the practical validation of the obtained results through the formulation of applied recommendations for industry enterprises regarding the optimization of high-efficiency quality management systems during the market's transition to the maturity stage.

#### **Presentation of the main research material**

The architecture of the developed whole-life-cycle quality management system is based on a two-level

hierarchical structure that integrates the strategic phases of product creation with a complex of innovative reliability assurance toolkits. At the core of the first level lies the determination of quality during the design and development stage, viewed as a fundamental preventive mechanism for the elimination of defects. Considering the thesis that up to seventy percent of quality characteristics and product costs are established during the research and development stage, the study substantiates a transition to a "source-based error minimization" strategy through the implementation of structured integrated product development processes and a multi-level system of quality gates. The process begins with strategic planning, where, based on benchmarking, consumer needs are converted into technical product requirement specifications, which serve as the regulatory basis for establishing target quality indicators. During the engineering modeling stage, these objectives are transformed into specific parameters using computer-aided engineering systems, while systematic failure prevention is implemented through the methodology of design failure mode and effects analysis and design verification plans. The final phase of the development stage includes the physical validation of prototypes under extreme conditions and the signing of production part approval process protocols, confirming the readiness of the manufacturing system for stable mass production.

The second level of the system is directed toward precision management of the direct manufacturing cycle, based on the concept of intelligent process control. The methodological basis of this stage is viewed as a synergy of management philosophies including total quality management, lean production, and six sigma, aimed at achieving zero defects and process stabilization within the "define, measure, analyze, improve, and control" cycle. The practical realization of this concept is ensured by the implementation of error-proofing technologies and a transition to intelligent inspection systems. The use of machine vision and laser metrology allows for the replacement of sampling control with one-hundred-percent online monitoring, guaranteeing unprecedented accuracy of results. A key tool for ensuring the transparency of the value chain is the end-to-end traceability system based on radio-frequency identification or quick response technologies, which forms a digital passport for each vehicle for rapid retrospective analysis of root causes of deviations. The integrity of the system is finalized by the supply chain collaboration strategy, which transforms relationships with contractors into a "quality community" through mechanisms of early supplier involvement and the use of advanced product quality planning standards, ensuring the homogeneity of product quality characteristics at all stages of its creation (tabl. 1).

Table 1

**Systemic Evolution of Quality Management Concepts (TQM, Lean, Six Sigma) in Reliability Assurance: From ICEV to NEV**

Comparison parameter	Traditional Paradigm (Industry 3.0 / ICEV)	Innovative Ecosystem (Industry 4.0 / NEV)	Methodological Significance (LSS-TQM Context)
Dominant control object	Mechanical units and assemblies (ICE, transmission) characterized by physical wear and tear.	Complex energy systems, Software, sensors, and cyber-physical modules.	Transformation of the control object from material-centric to intellectual-digital.
Quality management methodology	Reactive: defect detection during the final output stage (Post-inspection).	Proactive (Quality by Design - QbD): predictive modeling and failure prevention at the design stage.	Minimization of variability (6sigma) prior to the physical realization of the product.
Instrumental basis	Statistical Process Control, manual measurements, and control charts.	Digital Twins, Artificial Intelligence, CAE-simulations, and Big Data analytics.	Leveraging IT tools to radically reduce the impact of the human factor (error-proofing).
Supply chain configuration	Linear: suppliers act as executors of technical tasks based on rigid specifications.	Network-based (Early Supplier Involvement - ESI): deep R&D integration and component co-design.	Implementation of TQM principles by extending quality responsibility across the entire value chain.
Service support model	Reactive Maintenance: repair or replacement performed after a failure occurs.	Predictive Diagnostics and Over-the-Air (OTA) software updates via cloud technologies.	Continuous reliability management throughout the entire operational lifecycle.
Critical risk factors	Mechanical fatigue of materials, fluid leakages, and emission compliance.	Battery thermal stability, software bugs, and cybersecurity threats.	Necessity for implementing new standards of functional safety and digital resilience.

The comparative analysis demonstrates that ensuring the reliability of New Energy Vehicles necessitates a fundamental transformation of classical management approaches. The transition from reactive control of mechanical assemblies toward the proactive management of complex cyber-physical systems within the LSS-TQM cycle enables not only the mitigation of risks during the design phase but also the sustainment of the object’s viability through predictive diagnostics and digital updates. Consequently, the integrated Industry 4.0 model establishes a new quality ecosystem where reliability emerges from the synergy between high-end technologies and agile management methodologies.

At the same time, the successful implementation of such a model is unattainable without creating a specific organizational environment that supports the integrity of information flows and the agility of decision-making. This necessitates the introduction of tools that extend beyond purely engineering calculations and pertain to the enterprise's managerial architecture. Therefore, auxiliary elements of the quality management system acquire particular significance, as they ensure the coordination of efforts among all participants in the value creation chain.

Supporting elements act as a catalyst for integrating high-tech reliability standards into the daily operations of an enterprise. Let us examine them in greater detail within the scope of this study. Naturally, the primary role among the analyzed elements is held by management leadership and strategic commitment, which serves as the system's foundation in formulating a clear quality strategy. Senior management must not only provide the necessary financial and technological resources but also transmit the values of continuous improvement through personal example. A key aspect is the cultivation of a "non-blaming culture," which encourages transparency in defect reporting and focuses team efforts on identifying the systemic root causes of failures rather than the personification of responsibility.

Equally important is the element of cross-functional interaction and communication mechanisms. The structural complexity of New Energy Vehicles (NEV) necessitates the overcoming of traditional departmental silos; this is achievable through the development of a matrix management structure and the involvement of cross-functional teams, where engineers, software

developers, and quality specialists work in parallel. Process synchronization is ensured via institutionalized communication platforms and a unified information space based on PLM (Product Lifecycle Management) and MES (Manufacturing Execution Systems). Such integration allows for the unification of a "quality language" and ensures the continuity of data transfer among all project participants.

The third, yet equally vital element, is personnel development and the enhancement of corporate intellectual capital. The shift in focus toward cyber-physical systems requires a constant evolution of personnel competencies. Therefore, the implementation of a multi-level professional training system is proposed, covering both classical control tools (SPC, MSA) and predictive analysis methods (FMEA for software and power systems). Beyond technical training, it is critically important to foster a high level of quality awareness and establish clear career trajectories for specialists, which serves as a powerful motivational factor for retaining the enterprise's expert potential. The key findings and the systematization of the supporting elements of the quality management system, which ensure the coordination of efforts among all participants in the value creation process, are presented in Fig. 1.

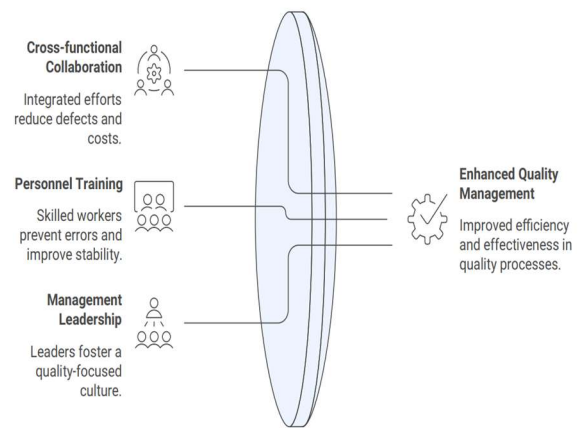


Fig. 1. Conceptual model of integrating supporting quality management elements to enhance NEV reliability

The successful implementation of the integrated LSS-TQM cycle relies on the synergy between technical instruments and organizational culture. Converting cultural factors into measurable metrics enables an objective assessment of the effectiveness of the quality management system's supporting elements (table 2).

Table 2

**Impact of Organizational Cultural Factors on the NEV Quality Management System**

Cultural Factor	Influence on Quality System	Key Performance Indicator (KPI)
Cross-functional Collaboration	Minimizes the gap between the design phase and real-world manufacturing, fostering parallel engineering.	Time-to-Change / ECR Frequency (Engineering Change Request frequency)
Personnel Training	Reduces process variability and mitigates risks associated with the "human factor" in complex assemblies.	First Pass Yield (FPY) (The percentage of products that meet quality standards without rework)
Management Leadership	Ensures adequate resource allocation and maintains a strategic focus on the "Zero Defects" philosophy.	Cost of Quality (CoQ) (Total costs related to preventing, detecting, and remediating defects)

Table 3

**Global NEV Market Dynamics and Strategic Positioning of Key Stakeholders (Forecast for 2025)**

Region / Company	Production/Sales Volume (2025)	Market Share	YoY Growth	Market Role & Strategic Impact
China (Total)	13.8 – 15.3 million units	~64%	+18.8% – 29%	Global manufacturing and export epicenter; NEV penetration has exceeded 50% of the domestic market.
BYD	~4.12 – 4.6 million units	~19.9 – 22%	+7% – 14%	Global leader; aggressive diversification from budget to ultra-premium segments.
Tesla	~1.64 million units	~7.6 – 10%	-8.6%	Technological pioneer facing stagnation due to a lack of mass-model refreshes.
Geely Group	~2.22 million units	~10.4%	+56.8%	Rapid expansion driven by premium sub-brands (Zeekr, Volvo) and high-volume mass models.
Europe (EU+UK)	4.26 million units	~19.8%	+34.9%	Market recovery; shift toward localizing Chinese production (e.g., BYD's plant in Hungary).
North America	1.74 million units	~8.1%	-5.0%	Demand cooling due to tax credit reversals; Hyundai emerging as a top-3 contender.
Asia (excl. China)	~1.23 million units	~5.7%	+58.5%	India and Indonesia emerging as new hubs for affordable electric mobility.
Global Total	~21.47 million units	100%	+21.5%	Market pivot toward pragmatic solutions and mass adoption of 800V architectures.

In summarizing the results of the conducted analysis, it should be noted that the efficiency of the integrated LSS-TQM cycle in NEV production is directly determined by the maturity level of the enterprise's organizational culture. The transformation of «soft» factors—such as cross-functional collaboration, continuous personnel training, and strategic leadership—into measurable Key Performance Indicators allows for the shift of subjective management aspects into the realm of objective monitoring and control. It has been established that the synergistic effect derived from minimizing engineering changes through parallel engineering, stabilizing the First Pass Yield, and optimizing the Cost of Quality forms a resilient reliability ecosystem. In this system, quality is viewed not as a result of final inspection, but as a derivative of the excellence of organizational interactions. Thus, the development of supporting

management elements is an indispensable condition for successful digital transformation and ensuring the global competitiveness of high-tech products under Industry 4.0 conditions.

However, the necessity for such an organizational transformation becomes even more evident when subjected to a quantitative "stress test" based on projected market dynamics. Given China's projected production scale of 34.5 million vehicles by 2025, the exponential impact of even minor quality deviations represents a critical business risk. Within a traditional reactive management paradigm, a seemingly negligible defect rate of 0.1% would result in more than 34,000 defective units entering the market annually. This volume of failures entails not only massive financial liabilities regarding warranty claims but also irreversible reputational damage within a hyper-competitive global ecosystem.

Such a scale of operations necessitates a transition to the Six Sigma methodology, where a target performance of 3.4 defects per million opportunities (DPMO) serves as the only viable operational standard. By shifting from a "detect-and-repair" logic to a proactive "Quality by Design" philosophy, manufacturers can mitigate these risks before production commences. Consequently, the implementation of the LSS-TQM framework is no longer merely a strategic advantage but a fundamental condition for survival and industry leadership in the era of mass-scale electric mobility.

The objective necessity of transforming quality management systems and implementing rigorous Six Sigma standards becomes most evident when extrapolating theoretical models onto the current scales of the global market. The transition from local production to mass global expansion requires not only technological readiness but also the capacity of management systems to withstand critical loads under hyper-competitive conditions. To provide a detailed analysis of the operational environment in which modern reliability ecosystems function, Table 3 systematizes the projected development indicators for key regional markets and the strategic roles of leading automakers. These data serve as a quantitative foundation for assessing the "Cost of Quality" risks on a global scale, where China's share as the primary manufacturing hub continues to dominate, shaping the developmental vectors of the entire industry.

It should be noted that the projected volume of 13.8–15.3 million NEV units is an integral part of China's extensive manufacturing ecosystem, the total capacity of which is estimated at 34.5 million vehicles by 2025. This implies that over 40–45% of the national production resources have already been reoriented toward high-tech cyber-physical systems. Such a shift effectively doubles the requirements for predictive quality control and the implementation of Six Sigma standards at every stage of the value creation chain. In this context, the stability of the LSS-TQM cycle becomes the decisive factor in mitigating the risks of mass-scale defects, which, at such volumes, could result in thousands of recalls and significant financial erosion.

**Conclusions.** The findings of this study provide a comprehensive substantiation of a synergetic quality management model for New Energy Vehicles (NEV), grounded in the integration of TQM, Lean, and Six Sigma paradigms. It is established that the transition toward software-defined and intelligent mobility necessitates a

radical shift in the management framework — moving from reactive control to a proactive, data-driven reliability architecture. A central element of this model is the evolution toward digitization and intellectualization, leveraging Big Data, AI, and Digital Twins to create a closed-loop, whole-life-cycle data ecosystem. This approach enables the continuous feedback of real-world usage data to the front-end development stages, ensuring that the "Quality by Design" philosophy mitigates up to 70% of potential risks before mass production commences.

The validity of the proposed model is further reinforced by a quantitative "stress test" based on China's projected market dynamics, with a total manufacturing capacity estimated at 34.5 million units by 2025. Calculations demonstrate that maintaining a traditional 0.1% defect rate would result in over 34,000 annual warranty claims, posing a direct threat to corporate reputational capital. Consequently, Six Sigma standards (3.4 DPMO) have evolved from a competitive advantage into a fundamental prerequisite for operational survival. Furthermore, the model emphasizes ecological quality collaboration, promoting open cooperation across the entire industrial chain to stabilize the First Pass Yield (FPY) and reduce process variability.

In conclusion, constructing a management system adapted to these modern requirements is the definitive path for the NEV industry to transition from "expanding scale" to "strengthening competitiveness." The synergetic fusion of technological innovation, intelligent closed-loop systems, and high managerial maturity remains the decisive factor for securing leadership and winning global competition in the era of high-tech electric mobility.

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### Хе Ке, Чорна О.Ю. Обґрунтування синергетичної моделі управління якістю нових енергетичних транспортних засобів у парадигмі концепції Tqm, Lean Ta Six Sigma

*У статті здійснено комплексне теоретико-прикладне обґрунтування синергетичної моделі управління якістю нових енергетичних транспортних засобів в умовах стрімкої технологічної трансформації та посилення глобальної конкуренції. Обґрунтовано зміну парадигми від традиційного реактивного контролю готової продукції до проактивної моделі управління повним життєвим циклом, що базується на концепції «Quality by Design». Доведено, що в умовах високої технологічної складності інтелектуальних систем електротранспорту, ізольовані методи інспектування втрачають ефективність, поступаючись системі «проекування–виробництво–сервіс». Наукову новизну дослідження становить концептуалізація інтегрованого інструментарію, що поєднує філософію TQM, інструменти Lean Production та точність Six Sigma. Деталізовано два стратегічні етапи трансформації, отже на етапі розробки: впровадження структурованих процесів та превентивних інструментів моделювання, що забезпечують усунення до 70% потенційних дефектів ще до*

початку серійного виробництва. У виробничому циклі: перехід до прецизійного управління через системи захисту від помилок (Рока-юке), автоматизовану інтелектуальну інспекцію та наскрізну простежуваність компонентів на основі RFID/QR-технологій.

Окрему увагу приділено інституційним та культурним детермінантам стабільності системи управління якістю. Обґрунтовано роль крос-функціональної взаємодії та лідерства як «м'якої» інфраструктури, що забезпечує подолання інформаційних бар'єрів та формування культури «якість понад усе». На основі порівняльного аналізу традиційних та інноваційних моделей управління доведено, що цифрова трансформація та використання Big Data є безальтернативними шляхами досягнення цільових показників надійності в масштабах масового виробництва. Отримані результати дають змогу сформувати стійку модель функціонування галузі в межах муніципальної та промислової екосистем, пропонуючи підприємствам механізми переходу від стратегії «нароццвання масштабів» до стратегії «високотехнологічної конкурентоспроможності» на світовому ринку.

**Ключові слова:** транспортні засоби на нових джерелах енергії; управління якістю; TQM; шість

сигм; система управління якістю; цифровізація; лідерство керівництва; превентивне управління; безперервне вдосконалення; план верифікації проєкту.

**Хе Ке** – аспірант за спеціальністю 073 менеджмент Східноукраїнський національний університет імені Володимира Даля, e-mail:

<https://orcid.org/0009-0008-1107-2348>

[men-23dd-315@snu.edu.ua](mailto:men-23dd-315@snu.edu.ua)

**Чорна Ольга Юрївна** – к.е.н., доцент кафедри публічного управління, менеджменту та маркетингу Східноукраїнського національного університету імені Володимира Даля,

<https://orcid.org/0000-0003-1976-4409>

e-mail: [chorna@snu.edu.ua](mailto:chorna@snu.edu.ua)

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