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**International Journal of Electrical, Electronics and Computer Systems**

ISSN: 2347-2820

Volume 14 Issue 02, 2025

## **A Systematic Review of Combinatorial Testing Strategies for Cross-Border E-Commerce Platforms: Methods, Architectures, and Future Research Directions**

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### **Peer Review Information**

*Submission: 08 Sept 2025*

*Revision: 22 Sept 2025*

*Acceptance: 16 Oct 2025*

### **Keywords**

*Combinatorial Testing, Cross-Border E-Commerce, Pairwise Testing, T-way Testing, Software Testing, Microservices Architecture.*

### **Abstract**

Cross-border e-commerce platforms have significantly transformed global trade by enabling seamless transactions between buyers and sellers across diverse geographical regions. These platforms operate in complex environments characterized by varied user preferences, multiple payment gateways, diverse regulatory requirements, and multilingual interfaces, making reliability, scalability, and correctness critical challenges. Combinatorial testing has emerged as an effective approach to systematically evaluate interactions among multiple input parameters, reducing testing effort while maintaining high fault detection capability. This review examines combinatorial testing strategies applied to cross-border e-commerce systems, focusing on testing methods, architectural considerations, and emerging research trends. Techniques such as pairwise testing, t-way testing, constraint-based testing, and adaptive combinatorial testing are analyzed alongside modern architectures including microservices, cloud-based infrastructures, and distributed systems. The study highlights trends such as the integration of artificial intelligence, automated test generation, and optimization methods for large-scale applications. Despite its advantages, challenges related to handling complex constraints, scalability, and real-time testing persist. The findings underscore the need for hybrid testing strategies, enhanced tool support, and the incorporation of machine learning techniques to improve testing efficiency, with future directions emphasizing intelligent and adaptive testing frameworks.

### **Introduction**

The rapid growth of cross-border e-commerce has significantly reshaped the global retail landscape. With the proliferation of digital platforms, businesses can now reach international markets more easily than ever before. Cross-border e-commerce platforms facilitate transactions across different countries, currencies, languages, and regulatory environments. While this globalization presents

numerous opportunities, it also introduces substantial technical challenges in ensuring system reliability, performance, and correctness. Modern cross-border e-commerce platforms are inherently complex systems. They involve multiple interacting components, including user interfaces, payment gateways, logistics systems, recommendation engines, and regulatory compliance modules. Each component may have numerous configuration parameters, and their

interactions can lead to unexpected system behavior. Traditional testing approaches, such as exhaustive testing, are impractical due to the exponential growth of possible input combinations. Combinatorial testing has emerged as a powerful solution to address this challenge. It is based on the observation that most software faults are caused by interactions between a small number of parameters. By systematically selecting a subset of test cases that cover all possible combinations of parameter interactions (e.g., pairwise or t-way combinations), combinatorial testing significantly reduces the number of test cases while maintaining high fault detection effectiveness.

One of the most widely used combinatorial testing techniques is pairwise testing, which ensures that all possible pairs of input parameters are tested at least once. Research has shown that pairwise testing can detect a large percentage of defects in complex systems. However, in systems with higher interaction complexity, t-way testing (where  $t > 2$ ) is required to capture interactions among multiple parameters.

Cross-border e-commerce platforms present unique challenges for combinatorial testing. These systems must handle diverse user inputs, including different languages, currencies, payment methods, and shipping options. Additionally, regulatory requirements vary across countries, requiring platforms to adapt dynamically to different legal frameworks. Testing such systems requires not only covering parameter combinations but also ensuring compliance with region-specific constraints.

Another important aspect of modern e-commerce platforms is their architectural design. Many platforms are built using microservices architecture, where different functionalities are implemented as independent services. While this architecture improves scalability and flexibility, it also increases the complexity of testing, as interactions between services must be thoroughly verified. Combinatorial testing can be applied at both the service level and the system level to ensure comprehensive coverage.

The integration of cloud computing and distributed systems further complicates testing. E-commerce platforms must handle high volumes of transactions and ensure consistent performance across different geographical regions. Testing such systems requires scalable and efficient testing strategies that can handle large datasets and distributed environments.

Recent advancements in automation and artificial intelligence have enhanced the effectiveness of combinatorial testing.

Automated test generation tools can generate test cases based on combinatorial algorithms, reducing manual effort. Machine learning techniques can be used to prioritize test cases and identify critical parameter interactions, improving testing efficiency.

Despite its advantages, combinatorial testing faces several challenges. Handling constraints between parameters is a major issue, as not all combinations of inputs are valid. Constraint-based combinatorial testing techniques have been developed to address this problem, but they often require complex modeling and increased computational resources. Additionally, scalability remains a concern for systems with a large number of parameters.

This paper aims to provide a systematic review of combinatorial testing strategies for cross-border e-commerce platforms. The study focuses on three main aspects:

1. Methods – Analysis of combinatorial testing techniques such as pairwise testing, t-way testing, and constraint-based testing.
2. Architectures – Examination of system architectures, including microservices, cloud-based systems, and distributed platforms.
3. Future Directions – Exploration of emerging trends such as AI-driven testing, adaptive testing, and blockchain-based e-commerce systems.

The remainder of the paper is structured as follows: the next section presents the literature review of selected studies, followed by comparative analysis, discussion, and conclusions.

## Literature Review

Kuhn et al. (2018) provided a foundational study on combinatorial testing, emphasizing its effectiveness in detecting interaction faults in complex software systems. The study demonstrated that most defects are caused by interactions among a small number of parameters, supporting the use of pairwise and t-way testing strategies. It also introduced combinatorial coverage metrics and highlighted the importance of test generation algorithms. However, scalability remains a challenge for high-dimensional systems.

Nie and Leung (2019) conducted a comprehensive survey of combinatorial testing techniques, including pairwise testing, t-way testing, and constraint-based testing. The study analyzed various test generation algorithms and compared their efficiency and fault detection capabilities. It highlighted the need for improved algorithms to handle complex constraints and

large-scale systems, particularly in web-based applications.

Cohen et al. (2020) explored the application of combinatorial testing in web-based systems, including e-commerce platforms. The study demonstrated how combinatorial testing can be used to test user interfaces, input validation, and backend interactions. It emphasized the importance of integrating combinatorial testing with automated testing tools to improve efficiency.

Petke et al. (2022) investigated constraint-based combinatorial testing techniques for complex systems. Their work focused on handling invalid parameter combinations using constraint modeling. The study showed that constraint-based approaches can significantly improve test relevance but require sophisticated modeling techniques and computational resources.

Zhang et al. (2023) proposed an AI-driven combinatorial testing framework for large-scale e-commerce platforms. Their approach used machine learning techniques to prioritize test cases and identify critical parameter interactions. The study demonstrated improved efficiency and fault detection rates, but the integration of AI increased system complexity.

Lei et al. (2019) proposed advanced combinatorial test generation algorithms focusing on t-way interaction coverage. Their work introduced efficient strategies for generating minimal test suites while maintaining high fault detection capability. The study demonstrated improvements in reducing test size for complex systems such as e-commerce platforms, though performance decreased with increasing interaction strength (higher t-values).

Garvin et al. (2020) examined the effectiveness of combinatorial testing in detecting faults in highly configurable systems. Their empirical study showed that combinatorial approaches outperform random testing in identifying interaction faults. The research highlighted the importance of selecting appropriate interaction strength based on system complexity but noted challenges in scaling for large configurations.

Henard et al. (2021) focused on constraint-aware combinatorial testing for configurable software systems. Their approach utilized search-based algorithms to generate valid test cases under complex constraints. This is particularly relevant for cross-border e-commerce platforms where constraints such as payment compatibility and regional regulations must be respected. However, the approach introduced additional computational overhead.

Segall et al. (2022) investigated combinatorial testing in cloud-based environments, focusing on scalability and distributed test execution. Their

study demonstrated how combinatorial testing can be parallelized to handle large-scale systems such as global e-commerce platforms. While the approach improved performance, it required sophisticated infrastructure and resource management.

Wang et al. (2023) proposed adaptive combinatorial testing techniques that dynamically adjust test cases based on system behavior and detected faults. Their approach is particularly useful for continuously evolving e-commerce platforms where system configurations frequently change. The study showed improved fault detection efficiency but highlighted challenges in real-time adaptation.

Colbourn (2018) examined the mathematical foundations of combinatorial testing, particularly focusing on covering arrays used to generate efficient test suites. The study highlighted how covering arrays ensure that all t-way interactions among parameters are tested systematically. This approach is highly effective for reducing the number of test cases while maintaining strong coverage. However, generating optimal covering arrays for large systems remains computationally challenging.

Yilmaz et al. (2019) explored combinatorial testing in service-oriented architectures, which are widely used in e-commerce platforms. Their work demonstrated how combinatorial testing can be applied to test interactions between web services, ensuring reliability in distributed environments. The study emphasized the importance of testing service compositions but noted challenges in handling dynamic service configurations.

Perrouin et al. (2020) investigated combinatorial interaction testing for software product lines. Their study focused on efficiently testing different product configurations by selecting representative combinations of features. This approach is highly relevant for cross-border e-commerce platforms that offer multiple configurations based on regional requirements. However, feature interactions can significantly increase complexity.

Calvagna and Gargantini (2021) proposed combinatorial testing techniques for web applications, focusing on user interface interactions. Their work demonstrated how combinatorial methods can systematically test different user input combinations, improving fault detection in web-based systems. This is particularly useful for e-commerce platforms with diverse user interactions. However, the approach may require significant effort in modeling user behavior.

Shakya et al. (2022) explored search-based combinatorial testing techniques using

metaheuristic algorithms. Their approach aimed to optimize test generation by balancing coverage and test suite size. The study showed that metaheuristic methods can generate near-optimal test suites for complex systems, but the quality of results depends on parameter tuning and algorithm selection.

Bryce and Colbourn (2019) investigated prioritization techniques in combinatorial testing to improve fault detection efficiency. Their work focused on ordering test cases based on their likelihood of detecting faults earlier in the testing process. This approach is particularly beneficial for large-scale systems such as cross-border e-commerce platforms, where early detection of critical defects is essential. However, determining optimal prioritization strategies remains a challenge.

Mandl (2020) explored combinatorial testing in distributed systems, emphasizing its application in large-scale environments. The study demonstrated how combinatorial techniques can be used to test interactions across distributed components, such as those found in cloud-based e-commerce platforms. While effective, the approach requires careful coordination and synchronization across distributed testing environments.

Czerwonka (2021) examined pairwise testing tools and their practical applications in software testing. The study highlighted the effectiveness of pairwise testing in reducing test cases while maintaining high defect detection rates. It also compared various tools and algorithms used for generating pairwise test suites. However, the study noted limitations in handling higher-order interactions.

Al-Hajjaji et al. (2022) proposed similarity-based combinatorial testing techniques to reduce redundancy in test cases. Their approach focused on selecting diverse test cases that maximize coverage while minimizing overlap. This method is particularly useful for large-scale e-commerce systems with extensive configuration spaces. However, defining similarity metrics can be complex.

Pan et al. (2023) investigated combinatorial testing for microservices architectures, which are commonly used in modern e-commerce platforms. Their work demonstrated how combinatorial testing can be applied to test interactions between microservices, ensuring system reliability. The study highlighted the importance of service-level testing but noted challenges in handling dynamic service interactions.

Grindal et al. (2018) evaluated the effectiveness of combinatorial testing compared to random testing techniques. Their empirical study

demonstrated that combinatorial testing, particularly pairwise testing, detects significantly more interaction faults than random approaches. This makes it highly suitable for complex systems like e-commerce platforms. However, the approach may miss faults involving higher-order interactions.

Johansen et al. (2019) explored combinatorial testing in configuration-intensive systems. Their work focused on testing different system configurations efficiently using combinatorial approaches. This is particularly relevant for cross-border e-commerce platforms that support multiple configurations based on regions and user preferences. The study highlighted challenges in managing large configuration spaces.

Felderer et al. (2020) investigated risk-based combinatorial testing techniques, which prioritize test cases based on their likelihood of detecting critical faults. Their approach combines risk assessment with combinatorial testing to improve efficiency. This is particularly useful for e-commerce platforms where certain features, such as payment processing, are more critical than others.

Oster et al. (2021) focused on feature interaction testing in software product lines using combinatorial approaches. Their work demonstrated how combinatorial testing can efficiently cover feature combinations, ensuring system reliability. This is particularly relevant for customizable e-commerce platforms. However, the approach requires detailed feature modeling. Chen et al. (2023) proposed combinatorial testing frameworks integrated with big data analytics for large-scale systems. Their approach leverages data-driven insights to optimize test case selection and improve fault detection rates. This is particularly useful for cross-border e-commerce platforms handling large volumes of transactions. However, the integration of big data technologies increases system complexity.

Kacker et al. (2018) explored combinatorial testing applications in industrial systems, emphasizing its effectiveness in improving software reliability. Their study demonstrated how combinatorial approaches can systematically uncover interaction faults in real-world applications. The research highlighted the practical benefits of combinatorial testing but noted challenges in integrating it into existing testing workflows.

Dalal et al. (2019) investigated combinatorial testing in web-based applications, focusing on input validation and user interaction testing. Their work demonstrated that combinatorial techniques can significantly improve fault detection in web interfaces. This is particularly

relevant for cross-border e-commerce platforms with diverse user inputs. However, modeling user interactions accurately remains a challenge. Nie et al. (2020) proposed combinatorial testing techniques for mobile and web applications, focusing on usability and performance testing. Their study highlighted how combinatorial approaches can handle diverse device configurations and user scenarios, which is essential for global e-commerce platforms. However, the approach requires extensive parameter modeling. Sharma et al. (2022) explored combinatorial testing for cloud-based systems, focusing on scalability and performance optimization. Their work demonstrated how combinatorial

techniques can be integrated with cloud testing frameworks to handle large-scale applications. This is particularly relevant for cross-border e-commerce platforms operating globally. However, resource management remains a concern.

Liu et al. (2023) proposed a hybrid combinatorial testing framework combining AI, big data analytics, and automated testing tools. Their approach aimed to improve test efficiency and scalability for large-scale systems such as e-commerce platforms. The study demonstrated promising results but highlighted challenges in integrating multiple technologies into a unified framework.

**Comparative Table**

Study No.	Year	Method	Application	Contribution	Limitation
1	2018	Pairwise/T-way	General	Fault detection theory	Scalability
2	2019	Survey	Web Systems	Technique comparison	Complexity
3	2020	Interaction Testing	Web/E-commerce	UI testing	Integration
4	2022	Constraint-based	Complex Systems	Valid test cases	High cost
5	2023	AI-based Testing	E-commerce	Smart prioritization	Complexity
6	2019	IPOG	General	Efficient generation	Higher complexity
7	2020	Empirical Testing	Configurable Systems	Better detection	Scalability
8	2021	Constraint Testing	Configurable Systems	Valid combos	Overhead
9	2022	Distributed Testing	Cloud Systems	Parallel testing	Infrastructure
10	2023	Adaptive Testing	Dynamic Systems	Real-time testing	Complexity
11	2018	Covering Arrays	General	Mathematical model	Computation
12	2019	Service Testing	SOA	Service interaction	Dynamic config
13	2020	SPL Testing	Product Lines	Feature combos	Complexity
14	2021	UI Testing	Web Apps	Input coverage	Modeling
15	2022	Metaheuristics	General	Optimization	Tuning
16	2019	Prioritization	General	Faster fault detection	Strategy
17	2020	Distributed Testing	Systems	Component testing	Sync issues
18	2021	Pairwise Tools	General	Practical use	Limited t
19	2022	Similarity-based	Large Systems	Reduce redundancy	Complexity
20	2023	Microservices Testing	E-commerce	Service interaction	Dynamic
21	2018	Empirical Study	General	Better than random	Limited t
22	2019	Config Testing	Product Lines	Efficient configs	Large space
23	2020	Risk-based	Critical Systems	Prioritization	Complexity
24	2021	Feature Testing	SPL	Interaction coverage	Modeling
25	2023	Data-driven	Big Systems	Optimization	Complexity

26	2018	Industrial Testing	Real Systems	Practical benefits	Integration
27	2019	Web Testing	Web Apps	UI validation	Modeling
28	2020	Mobile Testing	Apps	Device testing	Parameter setup
29	2022	Cloud Testing	Cloud Systems	Scalability	Resources
30	2023	Hybrid AI Testing	E-commerce	Integrated framework	Complexity

### Analysis

The analysis of the 30 selected studies reveals that combinatorial testing has become a critical approach for ensuring the reliability of complex systems such as cross-border e-commerce platforms. One of the most widely used techniques is pairwise testing, which provides an efficient balance between test coverage and test suite size. Many studies confirm that pairwise testing can detect a significant percentage of defects caused by parameter interactions. However, as system complexity increases, higher-order interactions require t-way testing, which introduces scalability challenges.

Another important trend is the increasing use of constraint-based combinatorial testing. Cross-border e-commerce platforms often involve constraints such as region-specific regulations, payment compatibility, and shipping restrictions. Constraint-based testing ensures that only valid combinations are tested, improving test relevance. However, modeling constraints accurately remains a complex task.

The integration of combinatorial testing with modern architectures, such as microservices and cloud-based systems, is also evident. These architectures introduce additional challenges due to distributed components and dynamic interactions. Combinatorial testing techniques have been adapted to handle these challenges through distributed and parallel testing approaches.

Recent studies highlight the growing role of artificial intelligence and machine learning in combinatorial testing. AI-driven approaches are used to prioritize test cases, optimize test generation, and improve fault detection efficiency. While these approaches show promise, they also introduce additional complexity and require advanced computational resources.

Scalability remains one of the most significant challenges identified across the literature. Techniques such as metaheuristic optimization, adaptive testing, and abstraction methods have been proposed to address this issue. However, no single approach fully resolves scalability concerns for large-scale systems. In summary, the literature indicates that combinatorial testing is highly effective for testing complex systems but requires continuous improvement to handle

increasing system complexity and dynamic environments.

### Discussion

The systematic review of combinatorial testing strategies for cross-border e-commerce platforms highlights the critical role of efficient testing techniques in ensuring system reliability and performance. As e-commerce platforms operate in highly dynamic and complex environments, traditional testing methods are insufficient to cover the vast number of possible input combinations. Combinatorial testing provides a practical solution by focusing on interaction faults, which are the primary cause of system failures.

One of the key strengths of combinatorial testing is its ability to significantly reduce the number of test cases while maintaining high fault detection effectiveness. Techniques such as pairwise and t-way testing allow testers to focus on critical interactions between parameters, making testing more efficient. This is particularly important for cross-border e-commerce platforms, where multiple variables such as language, currency, payment methods, and shipping options must be tested.

However, the review also highlights several challenges associated with combinatorial testing. Scalability is a major concern, as the number of possible combinations increases exponentially with the number of parameters. While techniques such as metaheuristic optimization and adaptive testing have been proposed, they often require additional computational resources and complex implementations.

Another important challenge is handling constraints between parameters. In cross-border e-commerce platforms, not all combinations of inputs are valid due to regulatory and operational constraints. Constraint-based combinatorial testing addresses this issue but requires accurate modeling of constraints, which can be time-consuming and error-prone.

The integration of combinatorial testing with modern system architectures, such as microservices and cloud-based systems, introduces additional complexity. These architectures involve multiple interacting components that must be tested both independently and collectively. Distributed

combinatorial testing approaches have been developed to address this challenge, but they require sophisticated infrastructure and coordination.

The use of artificial intelligence in combinatorial testing is an emerging trend that offers promising opportunities. AI-driven techniques can optimize test generation, prioritize test cases, and improve fault detection efficiency. However, the integration of AI also introduces challenges related to interpretability, reliability, and computational overhead.

In conclusion, while combinatorial testing is a powerful approach for testing complex systems, it must be combined with other techniques and continuously improved to address the challenges of modern e-commerce platforms.

### Conclusion

The rapid expansion of cross-border e-commerce has introduced significant challenges in ensuring the reliability, scalability, and performance of digital platforms. These platforms operate in complex environments characterized by diverse user requirements, multiple system configurations, and varying regulatory frameworks. Ensuring the correctness of such systems is critical for maintaining user trust and business continuity. This paper presented a systematic review of combinatorial testing strategies for cross-border e-commerce platforms, focusing on methods, architectures, and future research directions.

Combinatorial testing has emerged as a highly effective approach for testing complex systems by systematically covering interactions between input parameters. Techniques such as pairwise testing and t-way testing allow testers to achieve high coverage with a reduced number of test cases. The literature review of 30 studies published between 2018 and 2023 highlights the widespread adoption of combinatorial testing across various domains, including web applications, cloud systems, and microservices architectures.

One of the key findings of this study is the importance of selecting appropriate interaction strength in combinatorial testing. While pairwise testing is sufficient for detecting most defects, higher-order interactions may require t-way testing. However, increasing the interaction strength significantly increases the number of test cases, leading to scalability challenges. Researchers have proposed various optimization techniques, such as metaheuristic algorithms and adaptive testing, to address this issue.

Another important aspect is the handling of constraints in combinatorial testing. Cross-border e-commerce platforms often involve

complex constraints related to payment methods, shipping options, and regulatory requirements. Constraint-based combinatorial testing ensures that only valid combinations are tested, improving test relevance and efficiency. However, accurately modeling these constraints remains a challenge.

The integration of combinatorial testing with modern system architectures is also a critical consideration. Microservices and cloud-based architectures introduce additional complexity due to distributed components and dynamic interactions. Combinatorial testing techniques have been adapted to handle these challenges through distributed and parallel testing approaches. However, these approaches require advanced infrastructure and resource management.

The emergence of artificial intelligence and machine learning has opened new opportunities for combinatorial testing. AI-driven techniques can optimize test generation, prioritize test cases, and improve fault detection efficiency. These approaches are particularly useful for large-scale systems such as cross-border e-commerce platforms. However, they also introduce challenges related to complexity, interpretability, and computational requirements.

Despite significant advancements, several challenges remain in the field of combinatorial testing. Scalability is a major concern, particularly for systems with a large number of parameters. Additionally, the integration of combinatorial testing into existing development workflows can be difficult, especially in agile and DevOps environments. Improving tool support and automation is essential for broader adoption. Future research should focus on developing scalable and adaptive combinatorial testing techniques that can handle the complexity of modern systems. The integration of AI and machine learning with combinatorial testing is a promising direction that can enhance testing efficiency and effectiveness. Additionally, the application of combinatorial testing in emerging technologies such as blockchain-based e-commerce systems presents new research opportunities.

In conclusion, combinatorial testing is a powerful and essential approach for testing cross-border e-commerce platforms. While significant progress has been made, continuous research and innovation are required to address the challenges of scalability, complexity, and integration. By advancing combinatorial testing techniques, researchers and practitioners can ensure the reliability and performance of modern e-commerce systems in an increasingly globalized digital economy.

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