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APPLIED RESEARCH

# The Effects of Servitization, Digitalization, and Digital Learning Orientation on Sustainable Performance: A Hybrid PLS-SEM-ANN Model

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**ABSTRACT** Sustainability is a global concern. Industry 4.0 is driving the manufacturing sector toward sustainability within the Triple Bottom Line (TBL) framework, emphasizing economic, environmental, and social performance. However, limited empirical research has examined how servitization, digitalization, and digital learning orientation (DLO) interact to influence all three dimensions of sustainable performance. This study addresses this gap by proposing a tri-theoretical framework based on TBL, Resource-based View (RBV), and Dynamic Capability View (DCV). A hybrid partial least squares structural equation modeling-artificial neural network (PLS-SEM-ANN) model was developed to examine the direct effects of servitization and digitalization, the mediating effect of digitalization, and the moderating effect of DLO. An empirical analysis of 519 Chinese manufacturing employees revealed that servitization and digitalization positively impact sustainable performance, with digitalization acting as a mediating factor. Servitization also positively impacts digitalization. However, DLO negatively moderates the relationship between servitization and sustainable performance. A case study of Amazon.com, Inc. validates our quantitative findings by demonstrating the impact of servitization, digitalization, and DLO strategies on sustainable performance in real-world applications. These findings reveal theoretical and practical implications for effectively leveraging servitization, digitalization, and DLO to achieve practical sustainability.

**INDEX TERMS** Sustainable performance, servitization, digitalization, digital learning orientation, PLS-SEM-ANN.

## NOMENCLATURE

### *ABBREVIATION*

| | |
|---|---|
| $\alpha$ | Cronbach's alpha. |
| AI | artificial intelligence. |
| ANN | artificial neural network. |
| AVE | average variance extracted. |
| AWS | Amazon web services. |
| CFA | confirmatory factor analysis. |
| CI | confidence interval. |
| CMV | common method variance. |
| Coe | coefficient. |
| CR | composite reliability. |
| DCV | dynamic capability view |
| DIG | digitalization. |
| DLO | digital learning orientation. |
| DLO*DIG | interaction term combining DLO with digitalization. |

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| | |
|---|---|
| DLO*SER | interaction term combining DLO with servitization. |
| ECP | economic performance. |
| ENP | environmental performance. |
| FL | factor loadings. |
| HTMT | heterotrait-monotrait. |
| ICT | Information, communication & technology. |
| LLCI | lower limit confidence interval. |
| N1 | number of training samples. |
| N2 | number of testing samples. |
| NFI | normed fit index. |
| PLS-SEM | partial least squares structural equation modeling. |
| PLS-SEM-ANN | partial least squares structural equation modeling-artificial neural network. |
| $R^2$ | coefficient of determination. |
| RBV | Resource-based View. |
| RMSE | root mean square of errors. |
| SD | standard deviation. |
| SER | servitization. |
| SOP | social performance. |
| SP | sustainable performance. |
| SRMR | standardized root mean square residual. |
| SSE | sum square of errors. |
| TBL | Triple Bottom Line. |
| ULCI | upper limit confidence interval. |
| VAF | variance accounted for. |
| VIF | variance inflation factor. |

### SI UNITS

| | |
|---|---|
| g $CO_2e$ / GMS | grams of carbon dioxide equivalent per gross merchandise sale. |
| K | thousand. |
| M | million. |
| M metric tons $CO_2e$ | million tons of carbon dioxide equivalent. |

## I. INTRODUCTION

Sustainability is a global issue, requiring enterprises across sectors to balance short-term economic profitability with sustainable environment and social development. Industry 4.0 is propelling the manufacturing sector toward a more sustainable future by merging technological advancements with the Triple Bottom Line (TBL) (Elkington [18]) approach, which emphasizes the three dimensions of economic growth, environmental stewardship, and social well-being (Khan et al. [34], Li et al. [44], Sharma et al. [54]). While academic research has materialized and operationalized sustainability through the three TBL dimensions, balancing long-term economic growth, environmental conservation, and social development (Ghobakhloo [25], Purnamawati et al. [51]) remains challenging. Notably, Furstenau et al. [22] pointed out that the social dimension of sustainability has received less attention, revealing a gap in quantitative research that addresses the interplay among environmental, economic, and social dimensions. This highlights the need for research on integrated strategies to address all three dimensions of sustainability.

To address these gaps, this study investigates the roles of servitization, digitalization, and digital learning orientation (DLO) in influencing sustainable performance. Servitization, defined as the shift from offering products to providing product service bundles for competitive advantage Vandermerwe and Rada [59], and digitalization, which denotes the integration of digital technologies into business operations, are transforming the manufacturing industry, and impacting sustainable performance (Kohtamäki et al. [41], Xu et al. [65]). However, existing studies reveal mixed results regarding servitization's impact on performance (Neely [47], Kohtamäki et al. [41], Zhu et al. [73]), ranging from positive to negative, u-shaped (Zhou et al. [72]), s-shaped (Zhang et al. [71]), or context specific effects (Kharlamov and Parry [35]). Similarly, the digitalization paradox exists, and the complexities of digitalization's impacts remain incompletely understood (Broccardo et al. [10]). Therefore, the mechanisms of how servitization and digitalization influence sustainable performance remain incompletely explored (Doni et al. [17], Zhang et al. [70]), indicating a need for a more detailed empirical model.

In addition, while existing research has primarily examined the direct and indirect impacts of servitization and digitalization on firm performance (Kohtamäki et al. [41]), the moderating variables remain unexplored. Digital learning orientation (DLO), which focuses on continuous learning and capability development, is crucial for managing the uncertainties associated with digital and service oriented transformations. Although the moderating role of green DLO has been recognized in sustainable performance (Al Halbusi et al. [2]), its potential importance in driving servitization and digitalization remains underexplored.

This study addresses these gaps by seeking to answer three questions:

Q1: Do servitization and digitalization directly affect sustainable performance, and what is the relationship between servitization and digitalization?

Q2: Does digitalization mediate the relationship between servitization and sustainable performance?

Q3: What role does DLO play in the nexus of servitization, digitalization, and sustainable performance?

To address these questions, this study constructs an innovative tri-theoretical framework integrating TBL, Resource-based View (RBV), and DCV. A hybrid PLS-SEM-ANN approach applied to a sample of 519 Chinese manufacturing firms, enhances an understanding of how servitization, digitalization, and their interactions with DLO influence sustainable performance in the manufacturing sector. Furthermore, a case study of Amazon.com, Inc. validates the quantitative findings. The main contributions of this study are as follows:

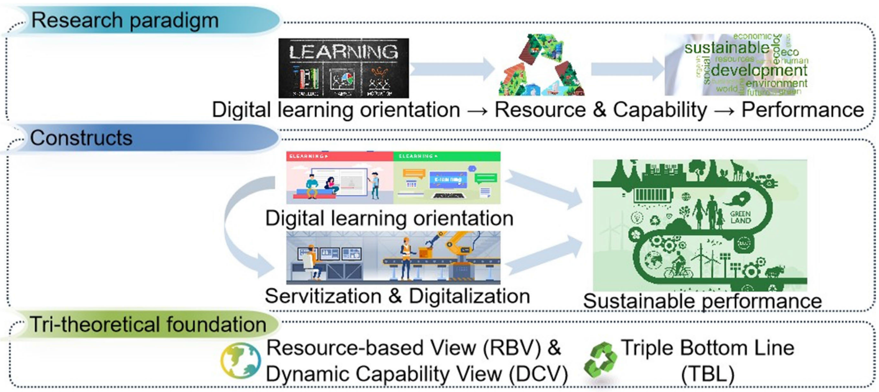



**FIGURE 1.** Theoretical foundation and research framework.

(1) The direct and indirect effects of servitization on sustainable performance are validated, establishing a comprehensive and integrated performance system through the TBL perspective.

(2) Digitalization is positively impacted by servitization, and its mediating role is found to differ in the direct and indirect effects of servitization on sustainable performance, emphasizing its importance in enhancing the benefits of servitization.

(3) The moderating role of DLO is investigated, revealing its negative moderation in the relationship between servitization and sustainable performance.

(4) The case study of Amazon.com, Inc. provides practical insights into how servitization, digitalization, and DLO strategies can be implemented in real-world contexts to achieve sustainability.

By combining quantitative findings with a real-world case study, this study provides valuable theoretical and practical insights into leveraging servitization, digitalization, and DLO to achieve sustainability. It also offers actionable guidance for businesses to balance profitability, environmental responsibility, and social impact in industrial practices.

The structure of this study is organized as follows. Section II reviews the related literature, and introduces the tri-theoretical framework. Section III proposes the research hypotheses. Section IV details the research methodology and data. Section V presents the findings of the PLS-SEM-ANN model and the case study. Section VI discusses the theoretical and practical implications, while Section VII outlines the limitations and directions for future research.

## II. THEORETICAL FOUNDATION AND RESEARCH FRAMEWORK

Servitization and digitalization have been frequently analyzed through RBV (Coreynen et al. [13], Zhang et al. [71]) and DCV (Civelek et al. [12]). To find out whether and how servitization, digitalization, and DLO affect sustainable performance, this study proposes a novel tri-theoretical framework based on the TBL, RBV, and DCV, which is consistent with the resource-capability-performance framework (Peng and Shao [49]). Inspired by the ‘‘oriented → capability → performance’’ pathway (Yang et al. [67]) and extending it, a ‘‘digital learning orientation → resource & capability → performance’’ research paradigm is constructed, as shown in Figure 1.

### A. SUSTAINABLE PERFORMANCE BASED ON TBL

TBL, proposed by Elkington [18] and subsequently utilized as a synonym for sustainability (Alhaddi [3]), emphasizes the balance among economic viability, environmental responsibility, and social welfare (Li et al. [44], Sharma et al. [54]). This framework underpins sustainable performance research, fostering a regenerative economy (Furstenau et al. [22]), and promoting enhanced environmental and social responsibility (Ghobakhloo [25]).

With the advent of Industry 4.0, the significance of servitization and digitalization in achieving sustainability objectives has been highlighted. Servitization aiming at sustainable development (Doni et al. [17]), complements TBL by adding value through sustainable service offerings. Concurrently, digitalization further amplifies TBL outcomes by promoting resource efficiency, reducing adverse environmental impacts, and fostering social inclusion for sustainable value (Khan et al. [34]).

In the Industry 4.0 context, the interplay between servitization and digitalization has become a crucial factor in sustainable performance, enabling manufacturing firms to achieve TBL's comprehensive sustainability goals through the integration of innovative services and digital solutions. Current research frequently separates the effects of servitization and digitalization on individual sustainability dimensions, underscoring the importance of an integrated approach to fully comprehend sustainable performance in manufacturing through the TBL lens.

### B. SERVITIZATION, DIGITALIZATION, AND DLO BASED ON RBV AND DCV

The integration of RBV and DCV creates a resource-capability framework (Ulaga and Reinartz [58]) for understanding servitization and digitalization, emphasizing the critical role of static resources and dynamic capabilities in realizing sustainability. DLO further extends this framework by highlighting the necessity of continuous learning and adaptation, to enhance resourcing capacities.

#### 1) INTEGRATION OF RBV AND DCV IN SERVITIZATION AND DIGITALIZATION

Integrating RBV with DCV offers a lens to evaluate how servitization and digitalization enhance manufacturing's TBL sustainability. RBV, focused on managing tangible and intangible resources for competitive advantage (Wernerfelt [62]), complements DCV's emphasis on reconfiguring capabilities for technological adaptation (Teece et al. [55]). This dual perspective highlights the need for manufacturing firms to possess unique and non-substitutable resources (RBV), and the capabilities to adapt, renew, and reconfigure these resources (DCV). Yang et al. [68] proposed that the resources and capabilities related to digitalization are needed to innovate the process of servitization. In our previous work, Bao et al. [7] pointed out that along with market economy reform, the capability to allocate resources through market-oriented measures was essential.

Some researchers have investigated resources (e.g., employee skills, digital strategy, etc.) (Eller et al. [19]) and capabilities (e.g., design-to-service, offering deployment, etc.) (Ulaga and Reinartz [58]), which are critical for digitalization and servitization. In particular, dynamic capabilities, as intangible resources within RBV, are considered essential for servitization and digitalization in manufacturing. However, how these resources and capabilities enhance sustainable performance is not fully explored.

#### 2) EXTENSION OF RBV AND DCV IN DLO

Under the RBV and DCV, essential resources and capabilities, such as practice-based knowledge and workforce skills, have been developed through experiential learning (Al Halbusi et al. [2]). DLO, which extends the concept of learning orientation, is crucial in the digital era. It emphasizes knowledge acquisition and application to seize digitalization opportunities and enhance firm performance. Kohtamäki et al. [39] further elaborated that continuous improvement and exploitative learning capabilities are essential for creating customized solutions, highlighting DLO's impact on servitization and digitalization.

While DLO is generally associated with long-term benefits, such as improved digitalization capabilities and enhanced organizational agility, it also imposes significant short-term resource demands. These demands include investments in digital infrastructure, employee training, and organizational restructuring (Teece [56]). This duality creates a paradox that DLO can simultaneously act as an enabler and a constraint on organizational performance, depending on the context and time horizon. For instance, in resource-constrained environments, the immediate costs of implementing DLO, such as financial strain and workforce reallocation, may outweigh its potential long-term advantages. This paradoxical nature of DLO aligns with the RBV and DCV frameworks. While DLO enhances capabilities like acquisition, assimilation, transformation, and exploitation (Zahra and George [69]), its implementation is resource-intensive. This can divert attention and resources from other areas, causing short-term inefficiencies (Barreto [8]).

Despite these challenges, DLO also creates opportunities for synergy between orientation, resources, capabilities, and performance. By integrating DLO into RBV and DCV frameworks, this study extends the application to explain how DLO impacts digitalization, servitization, and sustainable performance. For example, Fang et al. [20] pointed out that learning capabilities influence an organization's efficiency in resource allocation, while Iyer et al. [33] suggested that incorporating learning orientation into capabilities improves performance outcomes. These findings indicate that DLO is both an intangible resource and a dynamic capability, which enables manufacturing firms to develop digital skills, enhance service oriented transformations, and boost sustainable performance outcomes.

However, the role of DLO remains complex. On one hand, DLO equips firms with the capability to adapt to digitalization and servitization demands, improving long-term sustainable performance. On the other hand, its resource-intensive nature can hinder short-term performance, particularly in environments with limited resources or absorptive capacity. This duality underscores the need for a nuanced understanding of DLO's role in organizational contexts. Following the "digital learning orientation → resource & capability → performance" research paradigm (Figure 1), this study explores how DLO influences the interplay between servitization, digitalization, and sustainable performance, addressing the paradoxical and multifaceted nature of its impact.

## III. HYPOTHESES DEVELOPMENT

Based on the combined tri-theoretical framework, this study develops hypotheses on the direct and indirect effects of servitization, digitalization, and DLO on sustainable performance.

### *A. THE DIRECT EFFECT OF SERVITIZATION ON SUSTAINABLE PERFORMANCE*

Servitization, the shift from product-centric to service-centric operations (Kowalkowski et al. [42]), significantly influences sustainability in manufacturing. Its impact on financial and non-financial performance shows variability, with different research offering mixed findings, e.g., positive linear (Gebauer et al. [24]), U-shaped (Zhou et al. [72]), S-shaped (Zhang et al. [71]), etc. Despite the common belief in servitization enhancing operational efficiency, the "servitization paradox" suggests it may not yield expected financial returns (Neely [47]), indicating that servitization negatively impacts performance. This contradiction underscores the necessity for a more comprehensive analysis of the relationship between servitization and manufacturing performance.

It can also be drawn that as sustainable performance involves multiple factors to balance the three dimensions, the relationship between servitization and sustainable performance is complex. Therefore, new factors have been introduced to discuss the relationships. For example, Hao et al. [27] explored the combined effects of lean production and servitization on sustainable performance. Zhang et al. [70] demonstrated that servitization positively affects both environmental and social performance, highlighting the significant role of human resource slack and absorptive capacity. The moderating effect has also been explored. For example, Yang et al. [67] introduced corporate social responsibility as a moderator enhancing the impacts of servitization on firm performance. However, the direct effect of servitization on sustainable performance, especially its potential to enhance all three sustainability dimensions, remains unexplored.

From the RBV and DCV perspective, Zhang et al. [70] indicated servitization diminished dependency on tangible resources, improved resource reconfiguration capability, and enhanced economic, environmental, and social performance. Therefore, this study suggests that servitization may positively influence sustainable performance. The following hypothesis is proposed:

H1: Servitization has a positive impact on sustainable performance.

### B. THE DIRECT EFFECT OF SERVITIZATION ON DIGITALIZATION

The shift towards servitization relies on digital technologies to deliver services efficiently, and accelerates the practical adoption of digitalization. Kohtamäki et al. [41] discussed how servitization in manufacturing firms enhances their digitalization capabilities, as the complex services offerings require data analytics and other digital solutions. Servitization increases the need for digitalization to manage service complexities (Vendrell-Herrero et al. [60]), and servitization acts as a driver for digitalization innovation. It is found that manufacturing firms adopting servitization strategies often simultaneously enhance advanced digital capabilities to support service-oriented shifts. However, the existing studies tend to focus on how digitalization can boost servitization, and there is a lack of empirical research exploring servitization's role in advancing digitalization transformation.

Following the discussion of servitization's reliance on digitalization capabilities, this study assumes that servitization supports the enhancement of digitalization. Hence, the following hypothesis is proposed:

H2: Servitization has a positive impact on digitalization.

### C. THE DIRECT EFFECT OF DIGITALIZATION ON SUSTAINABLE PERFORMANCE

Digitalization has been increasingly recognized as a transformative force that significantly impacts sustainable competitiveness (Dabbous et al. [14]), by generating profits and reducing pollution. The interaction between digitalization and sustainability also raises concerns. For example, Ghobakhloo [25] proposed that digitalization contributes to manufacturing's sustainability, and creates sustainable job opportunities. Xu et al. [65] identified digitalization as a crucial organizational capability to promote eco-innovation and improve sustainable performance. This suggests the necessity for a detailed exploration of digitalization's contributions to manufacturing sustainability within the RBV and DCV framework.

Following the discussion of digitalization's positive impact on sustainable performance, this study assumes that digitalization can contribute positively to sustainability in manufacturing by enhancing predictive analytics capabilities, and optimizing resource utilization efficiency (Abou-Foul et al. [1]). Broccardo et al. [10] also confirmed the positive correlation between digitalization and sustainability. Hence, the following hypothesis is proposed:

H3: Digitalization has a positive impact on sustainable performance.

### D. THE MEDIATING EFFECT OF DIGITALIZATION BETWEEN SERVITIZATION AND SUSTAINABLE PERFORMANCE

Servitization and digitalization are analogous constructs to a certain degree (Vendrell-Herrero et al. [60]), with their significant interdependencies. Digital servitization, which describes the convergence between servitization and digital technologies, has become the new trend in manufacturing innovation (Kohtamäki et al. [40]). Kohtamäki et al. [41] investigated a nonlinear U-shaped relationship between servitization and digitalization on manufacturing firm performance. Coreynen et al. [13] demonstrated that digitalization could enable industrial, commercial, and value servitization. Martín-Peña et al. [45]validated the positive digitalization mediation effect between servitization and performance. Miao et al. [46] developed a moderated mediating model to prove that servitization significantly enhanced performance through digitalization. However, these studies have not fully explored the dynamic relationship between servitization and digitalization or adequately assessed their combined impact on the three dimensions of sustainable performance.

Based on the above discussion, this study proposes that digitalization can positively mediate the relationship between servitization and sustainable performance, and the integration of advancing digitalization can unlock the benefits of servitization. Based on the above discussion, the following hypothesis is proposed:

H4: Digitalization positively mediates the relationship between servitization and sustainable performance.

### E. THE MODERATING EFFECT OF DLO

DLO has been explored as a moderator (Setiawan and Heriyant [53]) in the relationship between employee engagement and outcomes, however, its role in servitization and digitalization remains unexplored.

This study aims to investigate the moderating role of DLO on the nexus among servitization, digitalization, and sustainable performance. It has been acknowledged that the integration of digital technologies into service oriented models underlines the necessity for organizational learning, highlighting the importance of DLO in servitization and digitalization. For example, Baines and Lightfoot [5] suggested that developmental training and improved knowledge acquisition were essential in servitization, highlighting the critical role of DLO in elevating service quality in servitization and sustaining a competitive edge in digitalization. It can be drawn that firms fostering a culture of continuous learning in the digital economy may effectively utilize digital servitization to improve sustainable performance.

However, the impact of DLO on long-term performance remains ambiguous. Baker and Sinkula [6] noted that developing a learning orientation was time consuming, and its effects on long-term performance were not instantly recognizable. To further explore the complex effect of DLO on the path connecting servitization, digitalization, and sustainable performance, the following hypotheses are proposed:

H5: DLO moderates the relationship between servitization and digitalization.

H6: DLO moderates the relationship between digitalization and sustainable performance.

H7: DLO moderates the relationship between servitization and sustainable performance.

Figure 2 shows the conceptual model and the hypotheses.

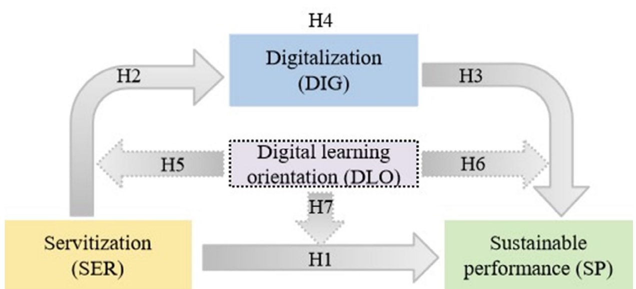



**FIGURE 2.** Conceptual model.

## IV. METHODOLOGY

### A. METHODOLOGY DESIGN

This study employs partial least squares structural equation modeling (PLS-SEM) and artificial neural network (ANN) to validate the developed hypotheses. PLS-SEM is selected due to its ability to clarify relationships among observed variables, and it has been commonly used for testing theoretical frameworks from a predictive standpoint (Hair et al. [26]). So it is suitable for evaluating the tri-theoretical framework in this study, specifically for investigating the "digital learning orientation → resource & capability → performance" research paradigm.

To overcome the limitations of PLS-SEM in detecting non-linear relationships, this study integrates it with ANN to develop the PLS-SEM-ANN model. PLS-SEM is effective for testing causal hypotheses, while ANN excels at identifying both linear and non-linear patterns. However, due to the "black box" nature of ANN, its direct use in hypothesis testing is limited. Therefore, this study integrates both methods, initially applying PLS-SEM to evaluate the conceptual model and hypotheses, followed by using ANN to rank the analysis outcomes.

Statistical analysis and ANN modeling are performed using SPSS 26, and SmartPLS 4.1 is used for model measurement and hypothesis testing. A case study of Amazon.com, Inc. is included to provide real-world validation. Amazon's practices in servitization, digitalization, and DLO are analyzed to demonstrate their impact on sustainable performance. Key performance metrics and sustainability outcomes from Amazon's annual reports are used to validate the conceptual framework.

### B. CONSTRUCT MEASUREMENT AND CONTROL VARIABLES

The sustainable performance (SP) measurement, comprising 13 items across three dimensions is derived from previous studies. Specifically, economic performance (ECP) is adapted from Yang et al. [66] and Davies et al. [15], environmental performance (ENP) is adapted from Benzidia et al. [9] and Wang et al. [61], and social performance (SOP) is adapted from Distelhorst et al. [16] and Li et al. [44]. Servitization (SER) is measured using 5 items from Abou-Foul et al. [1] and Hao et al. [27]. Digitalization (DIG) is assessed with 5 items from Abou-Foul et al. [1] and Proksch et al. [50]. DLO applies 4 items adapted from Hult et al. [32] and Benzidia et al. [9]. Detailed construct measurement items are provided in Appendix.

Consistent with Abou-Foul et al. [1] and Davies et al. [15], firm age, firm size, and industrial sector serve as control variables.

A 7 point Likert scale (1 = extremely disagree, 7 = extremely agree) is applied to reflect the viewpoint to each item, which was straightforward and collected with greater differentiation in responses (Willits et al. [63]) than the 5 point Likert scale.

### C. SURVEY AND DATA COLLECTION

A survey was conducted among Chinese manufacturing firms, selected for their participation in the "Made in China 2025" initiative, which aimed to enhance manufacturing capacity and sustainability (Li [43]). This initiative complements the shift towards green manufacturing and servitization, with China's "digital power" strategy emphasizing the critical role of digitalization in fostering sustainable development, which provides a practical context for examining the interplay between servitization, digitalization, and sustainable performance.

To ensure content validity, the questionnaire underwent a two-stage process. First, it was pretested with a small group of manufacturing employees to identify and modify the unclear or ambiguous items. Second, management scholars and industrial experts reviewed the revised questionnaire to evaluate its relevance and comprehensiveness. Given the

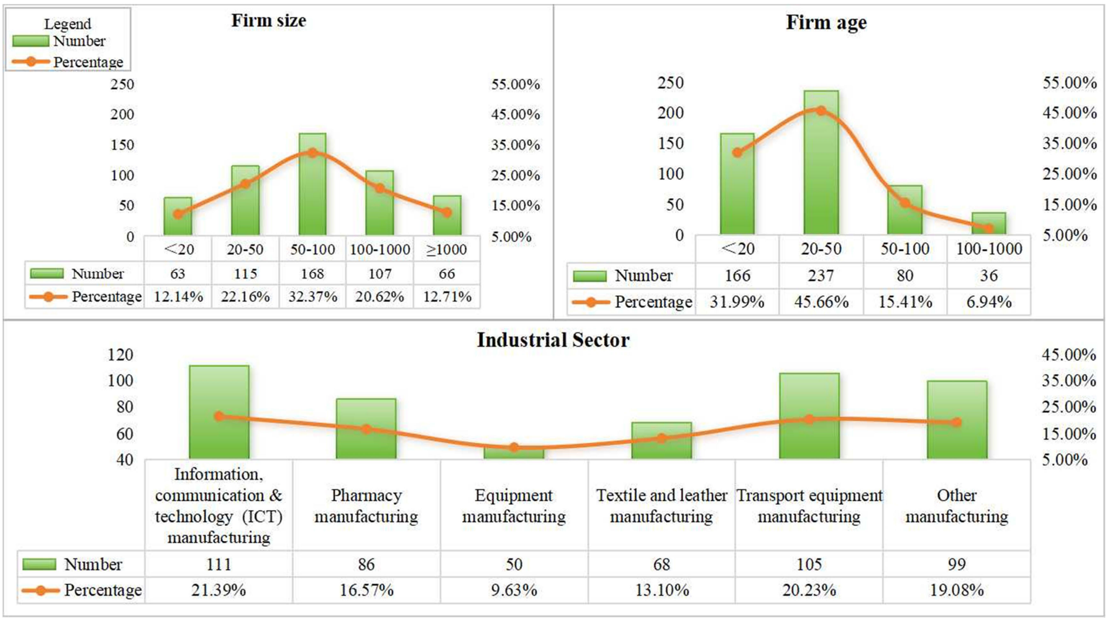



**FIGURE 3.** Sample characteristics.

**TABLE 1.** Measurement of construct.

| Construct | First-order item | Second-order item | FL | CR | AVE | α |
|---|---|---|---|---|---|---|
| Servitization (SER) | SER1 | | 0.8912 | 0.9321 | 0.7843 | 0.9313 |
| | SER2 | | 0.8788 | | | |
| | SER3 | | 0.8940 | | | |
| | SER4 | | 0.8780 | | | |
| | SER5 | | 0.8859 | | | |
| Digitalization (DIG) | DIG1 | | 0.8818 | 0.9289 | 0.7784 | 0.9288 |
| | DIG2 | | 0.8739 | | | |
| | DIG3 | | 0.8905 | | | |
| | DIG4 | | 0.8820 | | | |
| | DIG5 | | 0.8831 | | | |
| Digital Learning Orientation (DLO) | DLO1 | | 0.9002 | 0.9205 | 0.8071 | 0.9203 |
| | DLO2 | | 0.8999 | | | |
| | DLO3 | | 0.8966 | | | |
| | DLO4 | | 0.8968 | | | |
| Economic Performance (ECP) | ECP1 | | 0.9018 | 0.9231 | 0.8120 | 0.9228 |
| | ECP2 | | 0.8958 | | | |
| | ECP3 | | 0.9010 | | | |
| | ECP4 | | 0.9060 | | | |
| Environmental Performance (ENP) | ENP1 | | 0.8859 | 0.9302 | 0.7815 | 0.9302 |
| | ENP2 | | 0.8924 | | | |
| | ENP3 | | 0.8752 | | | |
| | ENP4 | | 0.8881 | | | |
| | ENP5 | | 0.8784 | | | |
| Social Performance (SOP) | SOP1 | | 0.9088 | 0.9250 | 0.8158 | 0.9248 |
| | SOP2 | | 0.8994 | | | |
| | SOP3 | | 0.9007 | | | |
| | SOP4 | | 0.9039 | | | |
| Sustainable Performance (SP) | | ECP | 0.8251 | 0.7577 | 0.6710 | 0.7538 |
| | | ENP | 0.7705 | | | |
| | | SOP | 0.8594 | | | |

survey's reliance on English based scales, a bidirectional translation process from English to Chinese and then back to English was conducted with volunteer assistance to ensure the precise expression of each item. To ensure linguistic accuracy, cultural and contextual differences were carefully addressed through iterative reviews and adjustments.

Data was collected via "Questionnaire Star" (https://www.wjx.cn), a leading survey platform in China. To enhance the quality and efficiency of sample collection, paid services were employed, targeting employees of manufacturing firms participating in the "Made in China 2025" initiative. Respondents need have at least 3 years of work experience in the field to ensure sufficient knowledge of servitization and digitalization. A total of 845 manufacturing employees were invited to participate in the survey, yielding 519 valid and completed responses, resulting in a response rate of 61.42%. The sample size meets the minimum requirement, maintaining at least a 10:1 ratio to the number of independent variables (Kock and Hadaya [37]). Figure 3 presents the characteristics of the samples.

### D. COMMON METHOD VARIANCE

Due to the single source samples in this study, common method variance (CMV) is a concern in questionnaire surveys. According to Kock [36], a variance inflation factor (VIF) value below 3.3000 indicates a model free from CMV concerns. The high VIF indicators are removed, following the recommendation of Kock and Lynn [38] to address collinearity issues in this study.

## V. RESULTS AND FINDINGS

### A. EVALUATING THE MEASUREMENT MODEL

The reliability of the measurement scale is first confirmed by Cronbach's $\alpha$ values exceeding 0.7538 for all measurement scales, as shown in Table 1, surpassing the recommended threshold of 0.7000 (Garver and Mentzer [23]), and indicating the high internal consistency of the questionnaire.

Following the methodology to assess the reflective measurement model (Hair et al. [26]), the PLS-SEM model is evaluated in four steps. The first step is to evaluate factor loadings (FL), with values above 0.7080 recommended. The second step involves evaluating internal consistency reliability through composite reliability (CR), with values between 0.7000 and 0.9500 recommended. The third step is to evaluate convergent validity, with an average variance extracted (AVE) above 0.5000 acceptable. The fourth step assesses discriminant validity using the heterotrait-monotrait (HTMT) ratio of correlations, following Henseler et al. [31], with threshold values set at 0.9000 or 0.8500 for distinct constructs.

A second-order confirmatory factor analysis (CFA), employing the maximum likelihood method, is applied to evaluate the reflective second-order construct. Rindskopf and Rose [52] argued that the second-order model was more restrictive and theoretically appealing, due to its explanatory power for higher correlations. Therefore, a second-order model is employed in this study to confirm the internal consistency of TBL theory, given the potential high correlations among the three dimensions of SP. This analysis utilizes 27 first-order items to assess six first-order constructs (DIG, SER, DLO, ECP, ENP, SOP), and three of which (ECP, ENP, SOP) are applied as second-order items, to form the second-order construct SP.

As shown in Table 2, the results reveal that all factor loading ranged from 0.7705 to 0.9088, surpassing the 0.7080 threshold, and confirming construct validity. Reliability and validity assessments of all constructs indicate CR values ranging from 0.7577 to 0.9321 are acceptable, because they exceed the 0.7000 benchmark, and are under the 0.9500 upper limit. Convergent validity, with AVE values for each construct, varies between 0.6710 and 0.8158, affirming the acceptable validity. Discriminant validity is indicated with the highest HTMT ratio ranging from 0.5457 to 0.6348, which is lower than the strict threshold value of 0.8500, as shown in Table 2.

**TABLE 2. Result of discriminant validity measures.**

| | SER | DIG | DLO | ECP | ENP | SOP |
|---|---|---|---|---|---|---|
| SER | **0.6155** | | | | | |
| DIG | 0.5999 | **0.5688** | | | | |
| DLO | 0.5188 | 0.5664 | **0.6304** | | | |
| ECP | 0.5976 | 0.5239 | 0.6304 | **0.6348** | | |
| ENP | 0.5554 | 0.5624 | 0.5072 | 0.4554 | **0.5457** | |
| SOP | 0.6155 | 0.5688 | 0.6027 | 0.6348 | 0.5457 | |

Note: The bolded numbers on the diagonal represent the highest values of HTMT ratios.

For adequate model fit, the standardized root mean square residual (SRMR) should be less than 0.0800, and the normed fit index (NFI) should exceed 0.9000 (Henseler et al. [30]). This model yields the SRMR value of 0.0392 (below 0.0800), and the NFI value of 0.9326 (above 0.0900), appearing to be adequate for the PLS-SEM model.

### B. HYPOTHESES TESTING BY PLS-SEM

The constructs and their items have been tested, meeting the standard requirements. Upon satisfactory assessment of measurement model, the next phase in PLS-SEM evaluation is to assess the structural model and test the research hypotheses.

This study employs the percentile method to construct 95% bootstrap confidence intervals (CI) with 5000 bootstrap samples. A CI excluding zero indicates statistical significance (Hayes [29]). Furthermore, t-value (t) limited by 1.9600 with a significance value of 5%, and 2.5760 with a significance value of 1% (Forza and Filippini [21]) are used, and p-values (p) are also presented in Table 3 to affirm the significance.

The structural model is validated by the p-values, t-values, and the 95% CIs. Servitization significantly influences sustainable performance ($t = 11.0330 > 2.5760$, CI = [0.3839, 0.5473]), supporting H1. Servitization also significantly influences digitalization ($t = 12.9257 > 2.5760$, CI = [0.4736, 0.6430]), supporting H2. Similarly, digitalization positively impacts sustainable performance ($t = 8.1824 > 2.5760$, CI = [0.2790, 0.4544]), supporting H3. Digitalization significantly mediates the relationship between servitization and sustainable performance ($t = 6.8298 > 2.5760$, CI = [0.1492, 0.2652]), supporting H4.

Figure 4 shows the coefficients for H1 ($a_1$), H2 ($b_1$), and H3 ($c_1$) are 0.4655, 0.5587, and 0.3647 respectively ($p = 0.0000 < 0.0100$), indicating significant direct effects. The indirect effect of servitization on sustainable performance through digitalization (H4) is calculated by Equation (1), with a coefficient ($M_1$) of 0.2038 ($p = 0.0000 < 0.0100$), confirming a significant mediation effect. The variance accounted for $VAF_1$ (Nitzl et al. [48]), calculated via Equation (2), shows that mediation explains 30.45% of servitization's total impact on sustainable performance. These findings demonstrate that servitization enhances sustainable performance directly, through value added services, and indirectly, by

**TABLE 3.** Results of mediation analysis.

| | Coe | SD | t-value | p-value | LLCI | ULCI | VAF | Results |
|---|---|---|---|---|---|---|---|---|
| *Total Effect* | | | | | | | | |
| SER → SP | 0.6693 | 0.0337 | 19.8491 | <0.01*** | 0.6037 | 0.7343 | | |
| *Total indirect effects* | | | | | | | | |
| SER → SP | 0.2038 | 0.0298 | 6.8298 | <0.01*** | 0.1492 | 0.2652 | | |
| *Direct Effects* | | | | | | | | |
| H1: SER → SP | 0.4655 | 0.0422 | 11.0330 | <0.01*** | 0.3839 | 0.5473 | | Accept |
| H2: SER → DIG | 0.5587 | 0.0432 | 12.9257 | <0.01*** | 0.4736 | 0.6430 | | Accept |
| H3: DIG → SP | 0.3647 | 0.0446 | 8.1824 | <0.01*** | 0.2790 | 0.4544 | | Accept |
| *Mediation Effects* | | | | | | | | |
| H4: SER → DIG → SP | 0.2038 | 0.0298 | 6.8298 | <0.01*** | 0.1492 | 0.2652 | 30.45% | Accept |

Note: *** t > 2.5760 of significance at 1% level (two-tailed), ** t > 1.9600 of significance at 5% level (two-tailed).

fostering digitalization capabilities (Vendrell-Herrero et al. [60], Zhang et al. [70]). It aligns with prior research on the synergistic effects of servitization and digitalization on sustainability (Kohtamäki et al. [40], Martín-Peña et al. [45]).

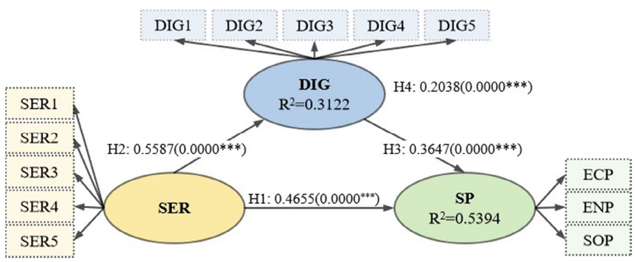



**FIGURE 4.** Mediation model.

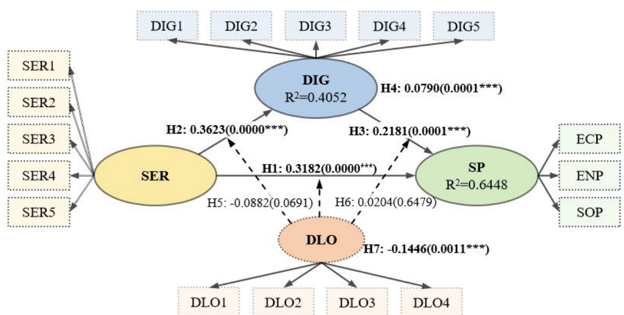
$$M_1 = b_1c_1 = 0.5587 \times 0.3647 = 0.2038 \tag{1}$$

$$VAF_1 = \frac{M_1}{a_1 + M_1} = \frac{0.2038}{0.4655 + 0.2038} = 30.45\% \tag{2}$$

To assess predictive power, the coefficient of determination ($R^2$) is applied, with values of 0.7500, 0.5000, and 0.2500 indicating substantial, moderate, and weak performance respectively (Hair et al. [26]). The $R^2$ values of 0.3122 and 0.5394 indicate that servitization has moderate and substantial predictive power for digitalization and sustainable performance, respectively.

The moderating role of DLO is partially supported, as shown in Table 4. DLO does not significantly moderate the effect of servitization on digitalization ($t = 1.8179 < 1.9600$, $CI = [-0.1831, 0.0081]$), rejecting H5. Similarly, DLO does not moderate the relationship between digitalization and sustainable performance ($t = 0.4567 < 1.9600$, $CI = [-0.0671, 0.1080]$), rejecting H6. However, DLO significantly moderates the impact of servitization on sustainable performance ($t = 3.2620 > 2.5760$, $CI = [-0.2314, -0.0568]$), supporting H7. In resource-constrained environments, the immediate costs of DLO can overshadow its potential long-term advantages, thus leading to its negative moderating effect on sustainable performance. These findings align with the paradoxical perspective of technology renewal in digitalization, where short-term challenges may hinder immediate benefits (Wimelius et al. [64]).

Figure 5 illustrates the moderated model. With DLO included, the coefficients for H1 ($a_2$) and H2 ($b_2$) are 0.3182 ($p = 0.0000 < 0.0100$) and 0.3623 ($p = 0.0000 < 0.0100$), indicating weaker direct effects of servitization on sustainable performance and digitalization. Similarly, the coefficient for H3 ($c_2$) is 0.2181 ($p = 0.0001 < 0.0100$), indicating a weaker effect of digitalization on sustainable performance. The mediation effect is calculated by Equation (3), with a coefficient ($M_2$) of 0.0790 ($p = 0.0001 < 0.0100$). It explains 19.89% ($VAF_2$) of the total effect of servitization on sustainable performance, calculated by Equation (4), indicating a significant but reduced mediation effect of digitalization. The coefficient for H7 ($W_1$) is $-0.1446$ ($p = 0.0011 < 0.0100$). Equation (5) shows that, in the total effect of the interaction terms of DLO with servitization (DLO*SER), the moderation effect accounts for 88.22% ($VAF_3$). It indicates that DLO negatively moderates the relationship between servitization and sustainable performance. These findings reflect the paradoxical impact of DLO, where short-term costs and challenges hinder immediate benefits (Trushkina et al. [57], Wimelius et al. [64]).




Note: The hypotheses accepted are highlighted in bold.

**FIGURE 5.** Mediation and moderation model.

$$M_2 = b_2c_2 = 0.3623 \times 0.2181 = 0.0790 \tag{3}$$

$$VAF_2 = \frac{M_2}{a_2 + M_2} = \frac{0.0790}{0.3182 + 0.0790} = 19.89\% \tag{4}$$

$$VAF_3 = \frac{W_1}{\text{Total effect(DLO} * \text{SER} \rightarrow \text{úSP)}} = \frac{-0.1446}{-0.1639} = 88.22\% \tag{5}$$

**TABLE 4.** **Results of mediation and moderation analysis.**

| | Coe | SD | t-value | p-value | LLCI | ULCI | VAF | Results |
|---|---|---|---|---|---|---|---|---|
| *Total effects* | | | | | | | | |
| SER → SP | 0.3972 | 0.0405 | 9.7970 | <0.01*** | 0.3188 | 0.4792 | | |
| DLO * SER → SP | -0.1639 | 0.0451 | 3.6330 | <0.01*** | -0.2549 | -0.0777 | | |
| *Total indirect effects* | | | | | | | | |
| SER → SP | 0.0790 | 0.0207 | 3.8167 | <0.01*** | 0.0406 | 0.1223 | | |
| DLO * SER → SP | -0.0192 | 0.0125 | 1.5435 | 0.1228 | -0.0480 | 0.0015 | | |
| *Direct Effects* | | | | | | | | |
| H1: SER → SP | 0.3182 | 0.0476 | 6.6890 | <0.01*** | 0.2245 | 0.4124 | | Accept |
| H2: SER → DIG | 0.3623 | 0.0569 | 6.3669 | <0.01*** | 0.2532 | 0.4751 | | Accept |
| H3: DIG → SP | 0.2181 | 0.0541 | 4.0349 | <0.01*** | 0.1101 | 0.3250 | | Accept |
| *Mediation Effects* | | | | | | | | |
| H4: SER → DIG → SP | 0.0790 | 0.0207 | 3.8167 | <0.01*** | 0.0406 | 0.1223 | 19.89% | Accept |
| *Moderation Effects* | | | | | | | | |
| H5: DLO * SER → DIG | -0.0882 | 0.0485 | 1.8179 | 0.0691 | -0.1831 | 0.0081 | | Reject |
| H6: DLO * DIG → SP | 0.0204 | 0.0446 | 0.4567 | 0.6479 | -0.0671 | 0.1080 | | Reject |
| H7: DLO * SER → SP | -0.1446 | 0.0443 | 3.2620 | <0.01*** | -0.2314 | -0.0568 | 88.22% | Accept |

Note: *** t > 2.5760 of significance at 1% level (two-tailed), ** t > 1.9600 of significance at 5% level (two-tailed).

Despite these challenges, DLO improves the model's predictive power, with $R^2$ values increasing to 0.4052 and 0.6448, compared to 0.3122 and 0.5394 in the mediation model. This highlights DLO's explanatory value, and the necessity of a long-term perspective to unlock its full potential for value creation.

While DLO is expected to enhance organizational capabilities, its short-term effectiveness is constrained by knowledge gaps, resource limitations, and challenges in digital technology upgrades (Amoah et al. [4]). Insufficient digital expertise limits employees' ability to leverage DLO for servitization and digitalization. Organizational culture barriers further hinder employee engagement with DLO (Trushkina et al. [57]). Effective DLO implementation should balance short-term resource and capability constraints with long-term strategic benefits.

These results validate the effectiveness of the "digital learning orientation → resource & capability → performance" pathway. Aligned with the combined tri-theoretical framework of TBL, RBV and DCV, the servitization, digitalization and DLO, as particular resources and capabilities, directly or indirectly influence the sustainable performance.

### C. HYPOTHESES TESTING BY ANN

The ANN analysis conducted in SPSS, focuses on significant predictors identified by PLS-SEM. SP is the output neuron, with four variables as input neurons. These variables influence SP directly, as detailed in Table 4, including servitization, digitalization, and the interaction terms of DLO with digitalization (DLO*DIG) and servitization (DLO*SER). The ANN employs a two hidden layer architecture with sigmoid functions for output and hidden neurons, as shown in Figure 6. Normalization of inputs and outputs to [0, 1] is implemented to enhance training efficiency. To minimize overfitting, ten fold cross validation is employed, dividing the data randomly into an 80:20 ratio for training and testing.

The root mean square of errors (RMSE), is used to assess the ANN's accuracy, with lower values indicating better fit. The models yield a mean value of 0.1123 for the training dataset and 0.1089 for the testing dataset, with standard deviations of 0.0033 and 0.0125, respectively,

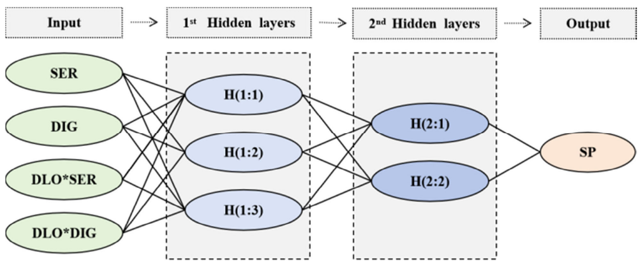



**FIGURE 6.** **Structure of ANN model.**

indicating high precision in the deep ANN model, as shown in Figure 7.

The sensitivity analysis indicates that servitization is the most significant predictor of sustainable performance, followed by DLO*DIG, as shown in Figure 8. This contrasts with the PLS-SEM results, which reject H6. The high normalized importance of DLO*DIG underscores the direct and mediating roles of digitalization, affirming the potential effect of DLO in the ANN models. The conflicting results stem from the methodological differences. PLS-SEM assumes linear relationships (Hair et al. [26]), and fails to detect insignificant linear moderating effects. In contrast, ANN can uncover hidden, nonlinear interactions (Chong [11]). The resource intensive nature of DLO may cause short-term inefficiencies. ANN's results suggest DLO's influence on digitalization and sustainable performance is complex and dynamic. This highlights the value of combining PLS-SEM and ANN to understand complex relationships. Hybrid approaches, as suggested by Hayat et al. [28], can overcome these limitations by combining PLS-SEM and ANN. This integration bridges linear and nonlinear analyses, offering deeper insights into causal relationships, especially in the presence of moderators or mediators. Together, they provide a more comprehensive understanding of sustainability predictors.

### D. CASE STUDY

To validate the quantitative findings, a case study of Amazon.com, Inc. offers the real-world context. As a global e-commerce leader in digital transformation and sustainable business practices, Amazon offers empirical evidence

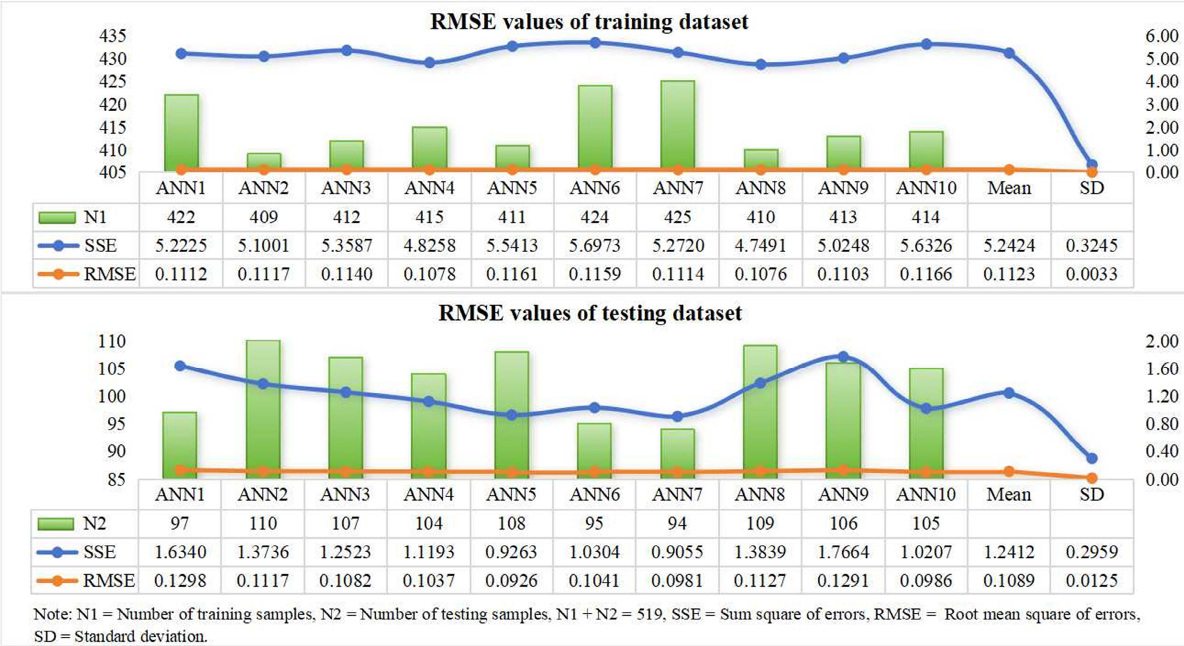



**FIGURE 7.** RMSE values of ANN models.

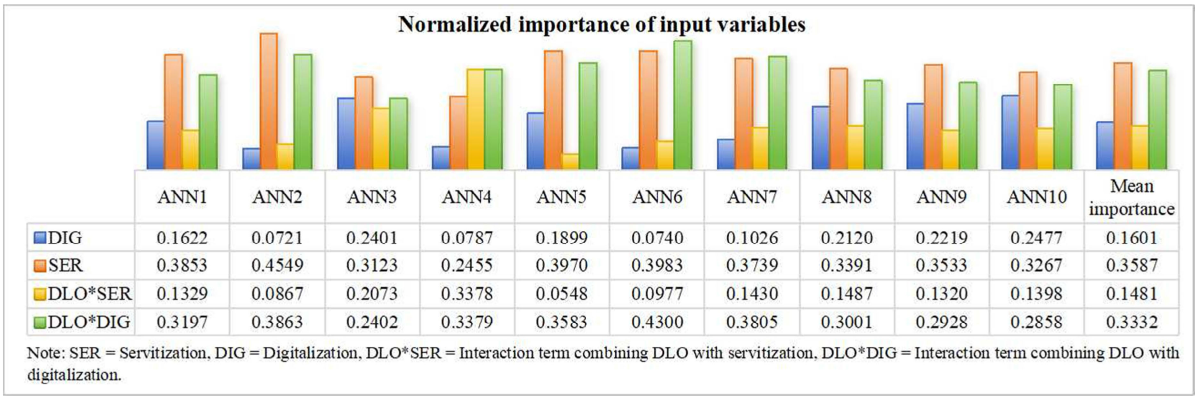



**FIGURE 8.** Normalized importance of input variables.

to validate the hypotheses. This case uses Amazon's publicly available annual reports and sustainability disclosures. Data in Table 5 are from its investor relations website (https://ir.aboutamazon.com), and sustainability website (https://sustainability.aboutamazon.com).

Amazon's servitization efforts are integrated with its digitalization strategy. A 17.64% growth in net service sales, and an 18.98% increase in third-party seller services, necessitate greater investment to enhance digitalization. Table 5 illustrates that infrastructure and technology investments in digitalization have grown by 16.95% to improve service offerings. It reflects how servitization drives digitalization, supporting H2.

Amazon's digitalization efforts have significantly improved sustainable performance. The Package Decision Engine, an artificial intelligence (AI) powered tool, reduces packaging waste and supports Amazon's sustainability goals. This digital supply chain optimization has led to a 2.71% reduction in absolute carbon emissions, a 13.12% decrease in carbon intensity, and a 5.65% reduction in the cost of sales ratio. These outcomes indicate the positive influence of digitalization on sustainable performance, supporting H3.

Digitalization also enhances the effectiveness of servitization in achieving sustainable performance. Servitization efforts, such as the Sustainability Solutions Hub, an online platform offering tools and resources for sustainable practices, rely on digitalization technologies like data analytics. Investments in digitalization, such as Amazon web services (AWS), a global data center, enable Amazon to scale its servitization initiatives. This leads to measurable improvements, such as reduced carbon emissions and increased sales. It highlights digitalization's mediating role between servitization and sustainable performance, supporting H4.

**TABLE 5. Comparison of amazon's metrics in 2022 and 2023.**

| Metric | 2022 | 2023 | Change |
|---|---|---|---|
| Total net sales (M) | 513983.00 | 574785.00 | 11.83% |
| Net product sales (M) | 242901.00 | 255887.00 | 5.35% |
| Net service sales (M) | 271082.00 | 318898.00 | 17.64% |
| Net sales of third-party seller services (M) | 117716.00 | 140053.00 | 18.98% |
| Climate Pledge Friendly products sold (M) | 818.00 | 1160.00 | 41.81% |
| Cost of sales (M) | 288831.00 | 304739.00 | 5.51% |
| Technology & infrastructure expenses (M) | 73213.00 | 85622.00 | 16.95% |
| Cost of sales / Total net sales (%) | 56.19 | 53.02 | -5.65% |
| Technology & infrastructure / Net sales (%) | 14.24 | 14.90 | 4.58% |
| Renewable energy percentage (%) | 90.00 | 100.00 | 11.11% |
| Carbon footprint (M metric tons $CO_2e$) | 70.74 | 68.82 | -2.71% |
| Carbon intensity (g $CO_2e$ / GMS) | 93.00 | 80.80 | -13.12% |
| Total employees (K) | 1541.00 | 1525.00 | -1.04% |
| People having received cloud computing skills training (K) | 13000.00 | 21000.00 | 61.54% |
| Employees upskilled (K) | 110.00 | 358.00 | 225.45% |
| Employees participated in Career Choice (K) | 100.00 | 175.00 | 75.00% |
| Employees upskilled percentage (%) | 7.14 | 23.48 | 228.87% |
| Employees participated in Career Choice percentage (%) | 6.49 | 11.48 | 76.84% |

Amazon's substantial investments in DLO demonstrate its resource intensive nature. Amazon has invested \$1.20 billion in employee upskilling programs, with participation increasing by 225.45% in 2023. Its free cloud computing skills training has reached 21.00 million people, reflecting a 61.54% increase. However, the rapid scaling of training programs cannot bring consistent returns. The investment in DLO may temporarily divert resources away from servitization's effect on sustainable performance. Additionally, the time consuming process of learning and adapting creates a steep learning curve for employees. These resource constraints and capability gaps explain why DLO fails to moderate the relationships in H5 and H6, and negatively impacts H7. Amazon's practices demonstrate that DLO aligns closely with long-term sustainable performance outcomes. The case study also highlights the potential drawbacks of excessive reliance on DLO, such as short-term resource strain and operational inefficiencies. These findings align closely with the survey results, reinforcing the observed relationships among servitization, digitalization, DLO, and sustainable performance.

## VI. DISCUSSION AND IMPLICATIONS

The empirical evidence from this study confirms the positive effects of servitization on sustainable performance (H1) and digitalization (H2), as well as digitalization's positive effect on sustainable performance (H3). Additionally, digitalization acts as a mediating factor (H4), with DLO serving as a moderator (H5-H7). The case study of Amazon demonstrates an alignment with the empirical findings. This investigation contributes to theoretical understanding and practical application within the manufacturing sector's shift towards sustainability in Industry 4.0.

### A. THEORETICAL IMPLICATIONS

The acceptance of hypotheses H1 and H2 emphasizes the crucial role of servitization in driving sustainable performance and enhancing digitalization capabilities, which is resonant with the RBV and DCV. Servitization, as a strategic resource, directly enhances sustainability through value added services, and acts as a catalyst for digitalization capability (Kohtamäki et al. [41]). H3, which confirms that digitalization positively impacts sustainable performance, is also supported. Amazon's servitization and digitalization strategies have significantly enhanced its sustainable performance, consistent with the positive effects identified in the PLS-SEM and ANN models.

The mediation role of digitalization in H4 aligns with DCV's focus on digital shifts in enhancing servitization to improve sustainable performance. However, comparisons between Table 3 and Table 4 reveal that the presence of DLO diminishes the positive impact of servitization on sustainable performance (H1) and digitalization (H2), as well as digitalization's direct impact on sustainable performance (H3), and its mediating effect between servitization and sustainable performance (H4). This extends the RBV and DCV framework, suggesting that the diversion of limited resources and capabilities might potentially weaken the impact of digitalization and servitization to achieve sustainability goals.

Contrary to expectations, this study reveals that DLO does not moderate the impact of servitization on digitalization (H5) nor the impact of digitalization on sustainable performance (H6). This could be attributed to the time intensive nature of DLO. DLO often lags behind the rapid pace of digital transformation, or integrates insufficiently with current capabilities. These findings indicate that firms should develop a holistic vision for managing their limited resources and capabilities under the tri-theoretical framework, rather than focusing on isolated aspects.

Additionally, different results of H6 from PLS-SEM and ANN models, indicate that digitalization might have a significant impact on sustainable performance, which overshadows the moderating effects of DLO. Sustainable performance is complex and comprehensive, influenced by multiple factors (e.g., organizational culture, management practices, etc.), and DLO may be just one potential moderating variable. The conflicting results highlight the methodological differences, as PLS-SEM focuses on linear relationships, while ANN captures nonlinear interactions. This divergence underscores the need for further research to fully reconcile these insights and better understand the dynamic interplay between variables and their impact on sustainability.

Notably, the negative moderation effect in H7 also challenges conventional RBV and DCV expectations. It indicates that while DLO is generally advantageous, it may consume excessive resources, or fail to align with the current digital practices or service oriented transformations in sustainability efforts. This finding extends the TBL framework, highlighting that not all efforts to integrate sustainability into business practices yield straightforward positive outcomes.

### B. PRACTICAL IMPLICATIONS

The empirical results also provide actionable insights for firms undergoing servitization and digitalization to navigate sustainable development effectively.

For manufacturing firms, strategically adopting servitization and digitalization is essential for sustainability in the Industry 4.0 era. The findings indicate that digitalization can amplify the effects of servitization on sustainable performance. Digitalization acts as a catalyst for servitization, fostering innovative business models (Kohtamäki et al. [40]). Employing digitalization to guide strategic servitization decisions can optimize resource allocation, enhancing sustainable performance. Recent studies by Eller et al. [19] on small and medium-sized marketing organizations in Austria, and those by Abou-Foul et al. [1] in the United States and Europe, have demonstrated that digitalization and servitization consistently influence sustainable performance across different geographical and cultural settings. Within the RBV and DCV framework, developing key capabilities and resources, particularly in digital infrastructure and workforce skills, is critical. For example, experienced managers play a crucial role in the successful implementation of servitization and digitalization strategies, as their dynamic capabilities in managing environmental uncertainties significantly enhance value creation. Therefore, manufacturing firms should prioritize intangible resources, such as human expertise, along with advanced digital capabilities, to innovate service offerings and enhance sustainability outcomes.

However, firms must address the negative moderation effect of DLO. Excessive focus on DLO can lead to resource constraints and capability diversion. To mitigate this, targeted training programs are essential to develop the workforce's capabilities for digital and service oriented transformations. This ensures workforce agility and alignment with strategic sustainability objectives. Organizations need to carefully calibrate their DLO initiatives to find the optimal balance between learning investments and operational efficiency. Both excessive and insufficient DLO can impede sustainable performance. This requires regular assessment of DLO outcomes against sustainability metrics, to ensure strategic alignment and resource optimization. A phased approach to integrating servitization and digitalization is recommended. It will help firms gradually enhance the necessary capabilities for sustainability. This study underscores the need for strategic approaches that integrate sustainability goals with servitization and digitalization capabilities, aligning with global trends toward environmentally conscious and digitally driven business models.

Amazon's case study expands the cross-industry applicability of the findings. It further demonstrates the importance of aligning digitalization strategies with servitization efforts to achieve sustainability. The increase in Amazon's servitization has amplified the strategic investments in digitalization, improving sustainability outcomes. Additionally, Amazon's experience highlights the necessity of balancing short-term resource constraints with long-term capability development, particularly in workforce upskilling and learning initiatives. It also highlights the critical role of strategic planning and phased implementation in managing the complexities of servitization, digitalization, and sustainable performance. Trushkina et al. [57] also highlighted that digitalization fosters innovative and customer-centric transformation, as evidenced by a case study from Ukraine. This demonstrates the model's generalizability by showing how digitalization reshapes organizational culture to adapt to diverse contexts.

For policymakers, supportive policies are essential to drive sustainable manufacturing. Regulations and incentives should promote servitization, digitalization, and effective DLO integration. Industry academia collaborations can foster innovation, while funding for digital and service oriented technologies can accelerate adoption. Tax incentives for sustainable practices can further encourage firms to invest in these strategies, aligning industrial growth with TBL objectives.

## VII. LIMITATIONS AND FUTURE WORK

This study proposes the tri-theoretical framework, enhancing the understanding of how servitization, digitalization, and DLO contribute to sustainable performance. However, it also encounters a few limitations. First, the data collection relies on perception-based 7 point Likert scale surveys. Although this study has added objective metrics from Amazon's case study, it still faces potential subjective bias. Second, the samples limited to Chinese manufacturing industries may affect the generalizability of the findings. Third, the conflicting results between the PLS-SEM and ANN models on DLO's moderating effects highlight the methodological constraints in certain fields.

Future research should combine quantitative metrics with qualitative assessments to enhance measurement validity. By incorporating longitudinal data and cross-contextual comparisons, future studies can further enhance the generalizability and practical relevance of the proposed framework. Longitudinal studies could provide insights into how the effects of servitization, digitalization, and DLO evolve into sustainable performance. Cross-industry and cross-cultural studies could help identify contextual factors that moderate the relationships within the model, thereby enhancing its applicability to a broader range of organizational environments. Additionally, studies should examine the resource allocation challenges and implementation barriers, to provide guidelines to balance short-term costs with long-term benefits. A measurement framework for DLO efficiency across diverse organizational contexts is also essential.

## SUPPORTING INFORMATION

The raw data for this paper has been uploaded to Figshare (https://doi.org/10.6084/m9.figshare.25778268).

## APPENDIX

### ITEMS OF CONSTRUCT

| Construct | Items | Reference |
|---|---|---|
| Servitization (SER) | SER1: Top management support plays a key role in service business orientation.<br>SER2: We invest in the necessary skills and capabilities to provide serviced offerings.<br>SER3: We systematically gather and analyze customer feedback, driving continuous improvement in our services.<br>SER4: We are actively building our service blueprints that involve serviced offerings.<br>SER5: We establish the new service concept, and focus on customer centric performance. | Adapted from Abou-Foul et al. [1] and Hao et al. [27] |
| Digitalization (DIG) | DIG1: We deliver products and services through digital channels.<br>DIG2: We constantly update and refine our digital strategy.<br>DIG3: We continually improve our core processes with the support of digital technologies.<br>DIG4: Our decision making processes are supported by data analytics.<br>DIG5: Our products and services demonstrate a higher degree of digitalization, compared to the competitors. | Adapted from Abou-Foul et al. [1] and Proksch et al. [50] |
| Digital Learning Orientation (DLO) | DLO1: The ability in digital learning is key to improving the firm's sustainable performance.<br>DLO2: Establishing effective sharing mechanisms helps to create a consensus across the organization on digitalization and servitization.<br>DLO3: The employees are motivated to acquire the necessary skills to further digitalize our company.<br>DLO4: We promote digital learning to prevent the digitalization process at risk. | Adapted from Hult et al. [32] and Benzidia et al. [9] |
| Sustainable Performance (SP) | *Economic Performance (ECP)*:<br>ECP1: Market share has grown faster.<br>ECP2: Profit has grown faster.<br>ECP3: Overall competitive position has grown faster.<br>ECP4: Operations costs have been reduced faster. | Adapted from Yang et al. [66] and Davies et al. [15] |
| | *Environmental Performance (ENP)*:<br>ENP1: Wastewater and hazardous waste emissions have decreased.<br>ENP2: Partnerships with many green suppliers have been established.<br>ENP3: The environmentally friendly purchase rate of goods and materials has increased.<br>ENP4: The investment in research and development (R&D) of environmental protection technology has increased.<br>ENP5: The green process planning supportive system has been actively adopted. | Adapted from Benzidia et [9] and Wang et al. [61] |
| | *Social Performance (SOP)*:<br>SOP1: Customers have increasingly trusted the products and services.<br>SOP2: The firm's image and brand value have been enhanced.<br>SOP3: The employees' education and training have increased.<br>SOP4: The workplace health and safety standards have improved. | Adapted from Distelhorst et al. [16] and Li et al. [44] |

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