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A Sustainable Digital Ecosystem: Digital Servitization Transformation and Digital Infrastructure Support

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Abstract: While the notion of digitalization and sustainability has become prominent in current research, more can be done to bridge these two concepts and explain the interaction between them. Plenty of literature has focused on the impact of digital technology applications and business model innovations on environmental performance but has not considered the counterforce of environmental performance on digitalization. We investigated this question from the perspective of digital ecosystem architects to explore more organic relationships. By analyzing data from 1083 listed firms from 2014 to 2019, we found various effective paths for architects to participate in the digital ecosystem and determined that improved environmental performance has led to more efficient convergence. Digital servitization adopted by private architects contributes to financial performance, whereas the addition of digital infrastructure enables public architects to play a greater role. This is reflected in the discovery that firms with "high" environmental performance can improve their financial performance far more significantly with the help of digital servitization compared to other firms. However, digital infrastructure development can benefit all firms almost indiscriminately. We encourage firms and governments to work together to strengthen digital infrastructure, build digital ecosystems, and focus on environmental performance while transitioning to digital servitization.

Keywords: digital ecosystem; digitalization and value cocreation; digital servitization; digital infrastructure; sustainability; environmental performance; financial performance

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1. Introduction

While the COVID-19 pandemic has led to the wider adoption of digitalization, determining ways to improve the efficiency and sustainability of digital ecosystems remains a concern [1,2]. In the theory of digital ecosystems, the sustainability strategy emphasizes multiple specialized areas. Recent research has focused on digital business models, digital marketing strategies, digital product innovations, social media analytics, and consumer value cocreations [1,3–5]. As these changes and innovations emerge, the concept of sustainability is no longer just concerned with the environment, but also a firm's ability to use digital technology, data resources, and service-dominant logic to continuously improve financial performance [6,7]. For example, a growing number of manufacturing firms are engaging in digital servitization (DS), a strategic transformation of business model, which optimizes processes, capabilities, and products through digital technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI) to create, deliver, and capture more added value with the associated ecosystem [3]. However, this continued company profitability is based on leveraging the resources in the digital ecosystem to obtain information and apply it to its own product–service innovations (PSI) [6,8]. It is not effective to improve financial performance only through DS [9]; ecosystem partnerships are critical for accessing digital capabilities, resources, and innovation to deliver DS [10–12].

The extant research has pointed out the problems firms face in achieving sustainable development through digital transformation [2]. Integrating into the digital ecosystem is already a complex task for manufacturing companies [13]. Consequently, while the potential for ecosystem collaboration is enormous, it is a fact that, in practice, most manufacturers engaged in DS struggle to reap any rewards [2,3,14].

This is not currently well discussed, but there is research that mentions the role of platforms and networks [15,16]. However, this is only part of the digital infrastructure. The hardware facilities, market size, potential users, talent pool, institutional efficiency, and communication environment all play huge roles [17–23] but are often discussed separately. We need to conduct further work to build a general framework to express the interaction between digital infrastructure and manufacturing firms. Environmental performance, as part of sustainability, can also affect a firm's profitability [24–26] by branding effects from social responsibility, consumer recognition from business ethics, and policy benefits from energy savings and emission reductions [24,25,27]. Although extensive research has been conducted in the area of environmental performance, there is still much to explore concerning the mechanisms of its impact on the digital ecosystem.

To bridge the knowledge gap and provide a practical reference, we focused on answering the following questions:

(1) What are the different types of participants involved in the process of building a digital ecosystem?
(2) What are the pathways through which these participants contribute to sustainability?
(3) What are the implications of sustainability for the operational mechanisms of digital ecosystems?

From the perspective of "ecosystem architects" theory [28], we constructed interactive theoretical models by deconstructing digital ecosystems into private and public architects and decomposing sustainability into financial and environmental performance. We analyzed the data of 1083 listed Chinese manufacturing companies from 2014–2019 and grouped them into different environmental performance levels. Through a panel vector autoregression (PVAR) [29] impulse response model and grouping comparison experiments, we obtained the dynamic interaction mechanism of digital ecosystems and sustainability.

The following chapters are arranged as follows: Section 2 introduces the theoretical analysis and research hypothesis. Section 3 covers the materials and methods. Section 4 presents the results of the data analysis for the effects of digital ecosystems on sustainability, along with insights into the research questions. Finally, Section 5 discusses the findings, contributions, and limitations of this study.

2. Theoretical Analysis and Research Hypothesis

2.1. Digital Ecosystems and Architects

In the digital age, the traditional cooperation networks of firms have gradually developed into a new ecosystem with cross-industry and complementary characteristics [30]. Digital ecosystems are often composed of multiple complementary firms that work together to achieve a common value proposition [31,32]. Current studies define digital ecosystems as "groups of architects contributing to a common value proposition" [33] (p. 2), where information and resources flow based on digital technologies and organizational support. On the one hand, public architects are the digital infrastructure that supports the operation of private architects, including digital platforms, cloud services, industrial Internet hardware infrastructure, and digital governance [34,35]. On the other hand, private architects are those who are active in the business, innovation, and platform ecosystems for profit and who provide technology to facilitate the development of the entire ecosystem [28]. Each architect within a digital ecosystem is interdependent but has "varying degrees of multilateral and non-generic complementarities which are not entirely controlled by hierarchy" [31] (p. 2264). In a digital ecosystem, digital businesses often require private architects from different industries and specialties to work together by providing different hardware devices or software services, whereas public architects such as platforms coordinate the activities of the various architects of the ecosystem through platform-centric loosely coupled partnerships [12,20]. Therefore, for a manufacturing firm, the digitalization that affects its performance has two aspects. One is its internal transformation as a private architect, digital servitization (DS). The other is external support provided by the public architects it works with, digital infrastructure construction.

The digital ecosystem emerged as a result of the development of the digital industry in the macroenvironment and the interaction of the various players in the ecosystem [28]. Traditional entrepreneurial, business, innovation, and platform ecosystems overlap, intersect, and permeate with each other to varying degrees to form the overall architecture of a digital ecosystem. Some scholars describe this dynamic as a coevolution of digital technology innovation and business model transformation [12,30,35]. Such transformation is an innovation in architects' collaboration models, organizational structures, and process coordination. Therefore, the ecosystem is hostage to its architects, whose digital technologies and business models reinforce their dominance while reshaping the evolution of the ecosystem from a traditional model to a digital economy model [15,36].

2.2. Digital Servitization: Sustainability Path for Private Architects

2.2.1. Private Architects in Digital Ecosystems

Over the past two decades, more firms have become private architects in digital ecosystems, which allows them to connect with other participants through platform networks to accelerate the expansion of firm boundaries and enable more efficient and richer access to information, knowledge, and data resources, which gives them a network advantage over external firms [37] through higher efficiency and competitiveness. Therefore, firms that were originally independent from the ecosystem must transform their original innovation model, value creation, and value capture in the face of the accelerating digitalization process of external collaborative networks [38] to integrate into the digital ecosystem and obtain this new firm-specific advantage, thus becoming private architects. These private architects provide additional data resources and technical support for broader innovative collaboration across the digital ecosystem [10,39].

2.2.2. Digital Servitization and Sustainability

DS is a strategic transformation where firms must move from a planned product-dominant logic to a collaborative service-dominant logic to adapt to the new production methods and collaboration models in the digital age [40]. This trend of convergence between servitization and digitalization leads to value chain changes and interconnections among different players that enable manufacturing firms to move along a transformation path that is influenced by both digitalization and servitization, which is defined as DS [41–43]. Current research suggests that digital technologies may affect the internal and external processes and interdependencies of firms [44], including value proposition, value network, and the revenue–cost structures in the business mode [45,46]. On the digitalization side, firms use digital technologies to manage their product and service operations more efficiently and to develop new value propositions, known as intelligent products, services, and solutions [8]. On the servitization side, manufacturing firms add customer-oriented services to their existing products [47].

As a path for private architects to participate in the digital ecosystem, DS connects internal organizations and external players to build a service system with technological mediation, continuity, and procedural interactions [48], where digital products serve as boundary objects of the service system to integrate the resources and activities of service providers and users and to facilitate their interactions and cooperation. This allows them to realize the dynamic allocation of resources [49] and to value the cocreation of service providers and users [50]. In DS transformation, private architects develop advanced business models through process innovation [51] and work closely with different stakeholders in a more advanced interactive way to become embedded in the digital ecosystem.

DS transformation can help companies upgrade their businesses by understanding what users care about through digital services, analyzing their facial microexpressions or reactions to specific content to learn how they perceive the company [52], and evaluating how they behave throughout the digital ecosystem [53]. Based on these results, the company can enrich its database and improve communication, increasing user retention and promoting sustainable business [54]. In addition, DS transformation can improve firms' financial performance [43,55–57]. In order to survive and excel in the modern business scenario, manufacturing firms must adopt digital technologies to achieve sustainable performance growth [58]. This is attributed to the fact that business process innovation may affect firm performance in the initial stages of implementation [59], whereas DS technologies in manufacturing can help improve the sustainability and efficiency of operations [60]. By applying digital technologies, manufacturing firms can increase productivity, flexibility, and responsiveness [61]. A series of benefits of DS on firm business development were identified [62]. For instance, firms carrying out DS can improve resource utilization, reduce their operational costs, generate additional revenues, maintain long-term business relationships with customers, and assess the risk of current product or service offerings [42], all of which are behaviors that can effectively improve the performance of a firm.

Hence, we propose the following hypothesis:

Hypothesis 1a (H1a). *The digital servitization transformation of private architects improves sustainability in financial performance.*

Environmental performance has the potential to influence the final outcome. Over the past few years, research has tied the sustainability of the company's growth to social recognition, consumer trust, and marketing strategies [5]. Environmental performance enables firms to build better brand images [63] and, consequently, improve customer loyalty [25]. This coincides with the characteristic of "proximity to the user" in DS transformation, where users are more willing to accept and pay for advanced service offerings and solutions due to trusting the brand [24], thus expanding their market share [25]. One of the earliest firms who obtained ISO14001 certification, Haier refrigerator, reestablished the image of "famous brand products" and "famous brand firm" auditing. Haier focused on developing fluorine-free and energy-saving environmental refrigerators while in the process of implementing ISO14001 and has achieved great success.

Hence, we propose the following hypothesis:

Hypothesis 1b (H1b). *Private architects with higher environmental performance are more effective at adopting digital servitization transformation.*

2.3. Digital Infrastructure: Sustainability Path for Public Architects

2.3.1. Public Architects in Digital Ecosystems

Public architects are integral parts of the digital ecosystem. Since firms, especially private firms, are organized for profit and must control costs, the resources and organizational capabilities required to build a digital ecosystem are far beyond their reach [9]. This requires the existence of "public architects" in the ecosystem that are not focused on their own financial performance and are not strategically anchored by technological developments and market potential to support the functioning of the entire ecosystem [28].

In contrast to private architects (firms) of digital ecosystems, digital infrastructure is a public product invested and constructed by public architects, such as the government or nonprofit organizations. It mainly focuses on the way the ecosystem is anchored in a specific spatial location or region and how it creates value for ecosystem stakeholders [28].

2.3.2. Digital Infrastructure and Sustainability

Digital infrastructure refers to the basic services necessary for a digital ecosystem to function properly, which includes technological ecology consisting of hardware (e.g., chips), software (e.g., operating systems, databases, etc.), cloud (e.g., cloud computing), and network (e.g., IOT, 5G), along with the social environment of digital tool users and the designers and system developers connected to the infrastructure [21]. The infrastructural services anchored within an area, such as a country, region, or city, influence the cost, reliability, and speed at which the digital ecosystem operates [28,64]. For firms, digital infrastructure is the important foundation for digital transformation in organizations that wish to enhance the potential of new digital technologies, mainly consisting of technical and organizational components, processes, and networks [7].

The construction of digital infrastructure can provide a low-cost path for resource flow and build a rational mechanism for trust exchange to improve the collaborative abilities of social environments, partners, and industry ecosystems [9]. New data architecture and open data have led studies to argue that broader public policies imply tighter corporate network locations [21]. New digital infrastructures (e.g., data analytics, cloud computing, and social media) facilitate this opportunity discovery process. However, the talent element is an important part of the overall digital ecosystem [21]. The continuous emergence of new technologies in the development of digital economies means that firms with more talent in digital technologies have a stronger production capacity and a better competitive advantage compared to their peers. Thus, technology and talent infrastructure play a central role in the digitization of industries and can positively influence the DS process of firms. Furthermore, current research confirms that tension or conflict in crowdsourcing systems or in the opportunity cocreation process encourage competition and cooperation among entrepreneurs [65]. Generating creative friction requires participants to be familiar with each other because there is tremendous pressure to discuss between strangers. The dialogue mechanisms of shared social platforms lower the threshold for mutual familiarity between strangers and can alleviate or resolve these pressures [65]. Therefore, new digital infrastructures allow groups of entrepreneurs to discuss and rapidly integrate in the process of business opportunity formation, while sharing and building new perspectives on top of each other's ideas or narratives [66].

The digital infrastructure level can influence the social productivity level [21], market demand [67], and business ecosystem network [30,68]. Due to the limitations of infrastructure level, such as the market environment, factor resources, and policy support, if the digital infrastructure can be strengthened, it can increase the resource reserves and reduce the cost of firms [21,69] to compensate for the lack of manufacturing infrastructure faced by firms to some extent [8].

Hence, we propose the following hypothesis:

Hypothesis 2a (H2a). *The digital infrastructure made by public architects improves the sustainability of the financial performance of local private architects.*

Environmental performance is achieved not only by establishing a sense of corporate social responsibility, but also by representing the management capability of a firm [70,71]. Firms who have attained ISO14001 can take advantage of their scientific model to improve the efficiency of management systems [26], including the rigor and effectiveness of practices, regulatory compliance, greener supply chain, and documentation control [70,71], so that their management level can be significantly improved and all aspects of control and responsiveness can be optimized [70]. Establishing a macroenvironmental management system is also a process of improving firms' ability to work in synergy with partners [11,32]. This process greatly increases employees' awareness of environmental conservation and willingness to communicate and share [72], which are very beneficial to the firm's overall use of social and public resources, especially infrastructure. Firms with higher environmental performance may be more willing and able to make digital infrastructure play a greater role.

Hence, we propose the following hypothesis:

Hypothesis 2b (H2b). *Private architects with higher environmental performance are more positively influenced by the digital infrastructure of public architects.*

Figure 1 shows all the hypotheses as a theoretical framework.

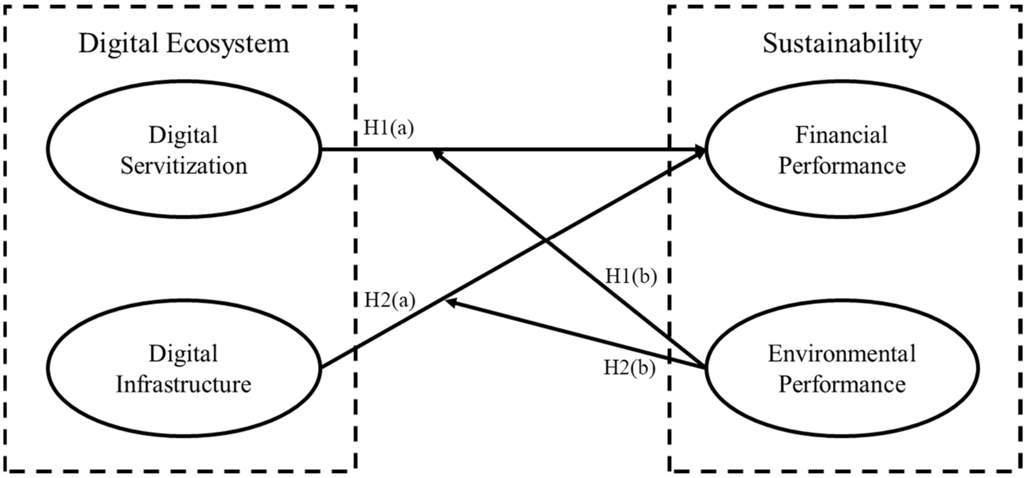

Figure 1. Theoretical framework.

3. Materials and Methods

3.1. Sample and Data

We selected A-share manufacturing firms as the research subject and used 2014–2019 panel data to investigate the various hypotheses. After data screening and cleaning, we obtained 2387 valid observations. A total of 1083 samples were taken from the CSMAR database, including all of the remaining A-share and non-ST manufacturing firms, after excluding the industries covered by the digital economy industry list of the National Bureau of Statistics, for a total of 1083. Specifically, in the first step, we screened and identified all manufacturing firms based on the "manufacturing" code in the National Economic Industry Classification, which includes 1640 non-ST listed firms in all manufacturing industries from C13 to C43 (GB/T 4754-2011). In the second step, we eliminated 557 samples of manufacturing firms that were born digital under the category of industry code C39 in the initial year (2014), leaving 1083 firms as potential subjects of digital transformation.

In addition, we matched the financial data of listed firms, the DS data obtained through text analysis of annual reports, and the digital infrastructure level data. The data were mainly extracted from the CSMAR database, the National Bureau of Statistics, the Data Center of the Shanghai Stock Exchange, and the Internet research institute. Among them, firm performance and related financial data were obtained from the CMSAR database, whereas DS data were obtained through textual and inductive analysis based on the content of the firm annual reports published by the SSE. The digital infrastructure data mainly refer to urban statistical reports released by national and local statistical agencies; it also includes public data released by the Tencent Research Institute, with statistics covering multiple digital platforms such as e-commerce, transportation, catering, and accommodation. Based on this, various types of data were aggregated and standardized to align the research methods with the statistical calibers to analyze the standardized aggregate data of 351 cities.

Finally, we matched the data from the different sources mentioned above by security code, year, industry, and region. Winsorize was performed on the 1% and 99% quartiles for continuous variables to eliminate the effect of outliers on the results.

3.2. Measurement of Variables

3.2.1. Measurement of Digital Servitization Transformation

Referring to related studies [42,73], the DS indicators were inscribed by the inductive research method. By collecting the annual statements of all of the sample firms from

2012–2019 and by conducting data mining and hierarchical text analysis based on the three-level coding aggregated thematic analysis framework of the inductive research method [42], the expressions containing first-order keywords within the list in the manufacturing firms' annual reports were counted as DS. Generally speaking, the higher the indicator, the higher the firm's degree of DS.

We collected and aggregated the information based on DS that was identified by the inductive research method in journal papers published from 2019–2022. We specifically included the basic units of case studies and text analyses and the key words and phrases used for inductive coding [9,42] to assemble them into a DS dictionary and to assign the words in the dictionary according to the number of occurrences. This allowed us to portray the development of a firm in the process of DS. Our integrated DS lexicon is portrayed in Table 1.

Table 1. Dictionary of DS (twenty of the most frequent occurrences).

Vocabulary, Frequency (Top 1–10)	Vocabulary, Frequency (Top 11–20)
Data, 58,035	Website, 7762
Smart, 31,019	Process, 7703
Digital, 22,241	Integration, 7329
Platform, 22,114	Information Technology (IT), 6712
Automatic, 17,131	Calculation, 4395
Cloud, 14,933	Digitalization, 3687
Integration, 9626	E-commerce 3490
Internet, 8683	Online 3401
Sense, 8237	Offline 2784
Customer, 7862	Computer Numerical Control (CNC), 2614

Source: developed by authors.

3.2.2. Measurement of Digital Infrastructure Support

Referring to current studies and related reports [7,66], we adopted the urban digital economy index to measure the level of digital infrastructure within the region in order to quantify the contribution of the public architects. This is a comprehensive index publicly provided by the Tencent Research Institute that includes multiple subindexes. It examines the operation scale of large digital platforms to reflect the production and supply level of local digital technology and support services [21], the number of Internet users to reflect the local market demand [67], and the digital governance level of the local government to reflect the trust mechanism [30,68].

3.2.3. Measurement of Financial Performance Sustainability

Referring to relevant studies [20], we chose return on assets (ROA) to measure the development of private architects' financial performance. Further, we observed whether firms were able to continue to profit over time through the dynamic statistical analysis model [20] to test the sustainable development of financial performance.

3.2.4. Measurement of Environmental Performance

Referring to current studies and relevant reports, we selected ISO14001 certification as an indicator of firms' environmental performance [25,26]. Firms that obtained ISO14001 certification are regarded as private architects with "high" environmental performance, whereas those that have not obtained ISO14001 certification belong to the group with "low" environmental performance. We present all the variables and related descriptive statistics in Table 2.

Table 2. Measurement and descriptive statistics.

Variables	Short	Mean Value	Standard Deviation
Digital Servitization Transformation	DS_Trans	42.1016	29.2422
Digital Infrastructure Support	DI_Support	5.5126	8.0122
Financial performance	Perf	0.0456	0.0520
Environmental Performance	ISO	0.2891	0.4534

3.3. Method

We realize there are some common influences between digital transformation and sustainability, such as management capabilities, dynamic capabilities, leadership traits, and corporate culture and cohesiveness. These variables are difficult to quantify and calculate in this model, which will make the model endogenous. Therefore, we chose the PVAR model for our analysis.

Based on the PVAR model [29], we performed impulse response functions through a Helmert transformation to ensure smooth data. This approach combines traditional VAR and panel data to allow for variable endogeneity and individual heterogeneity and to enable a reasonable explanation of the intrinsic relationship between variables.

4. Results

4.1. Effects of Digital Servitization under Different Environmental Performances

With DS transformation as the shock variable and financial performance as the response variable, we implemented 500 Monte Carlo simulations at 95% confidence intervals. This allowed us to obtain the impulse response relationship graph. The horizontal axis is the response period, which represents the time axis of the impact mechanism; the vertical axis is the estimated coefficient, which represents the return of the impact mechanism; the upper and lower lines are the two bounds of the confidence interval; and the impulse response function point estimates are the curves in the middle of the figure.

Figure 2 shows the graphs of impulse responses for a model with two variables (digital servitization of private architects and their financial performance) estimated for all samples. Figures 3 and 4 report the same model for a sample of private architects with “high” environmental performance and a sample of private architects with “low” environmental performance.

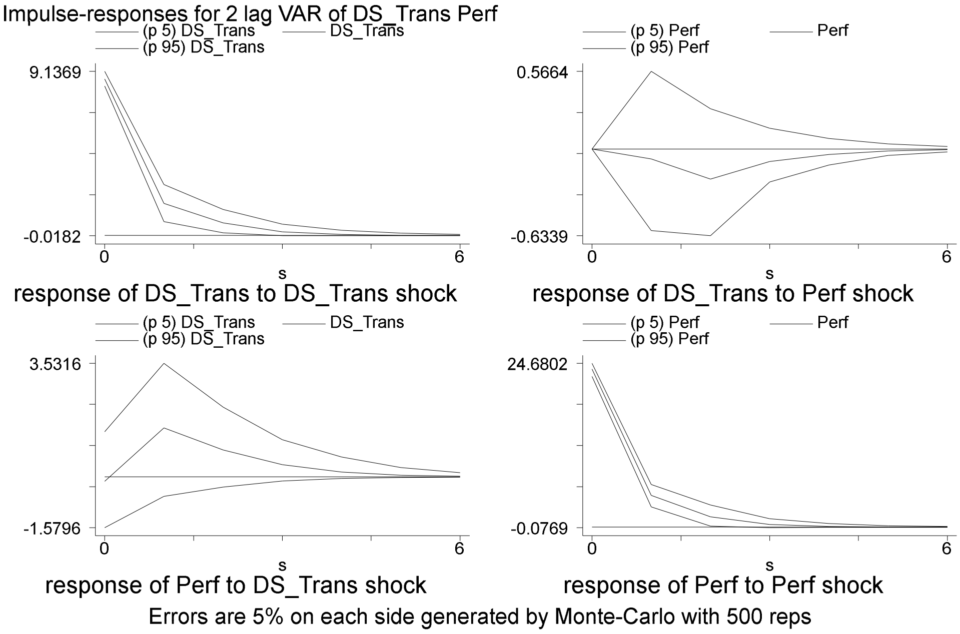

Figure 2. Impulse responses for the sample of all private architects (model of DS transformation and financial performance).

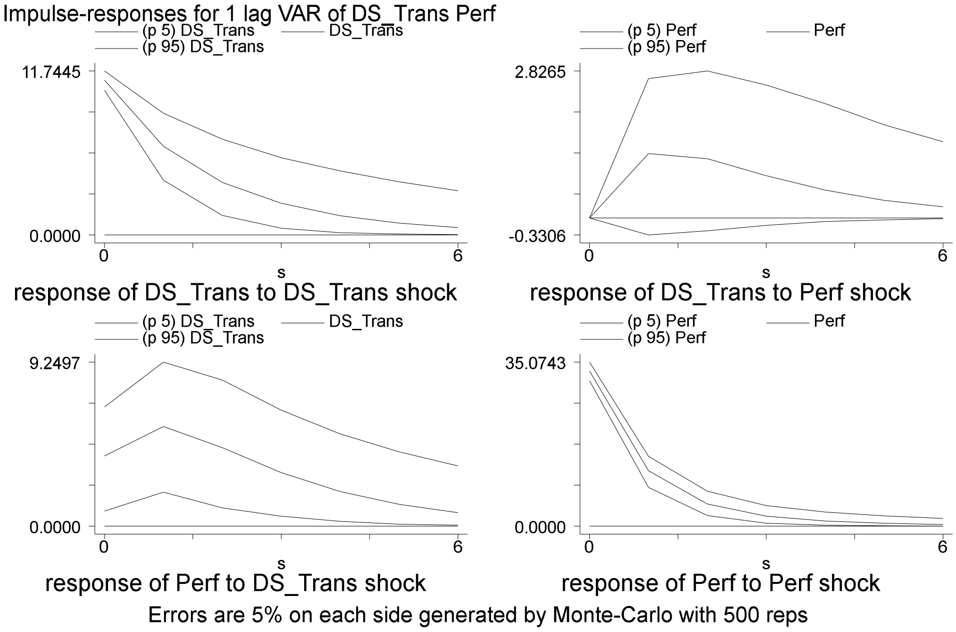

Figure 3. Impulse responses for private architects with "high" environmental performances (model of DS transformation and financial performance).

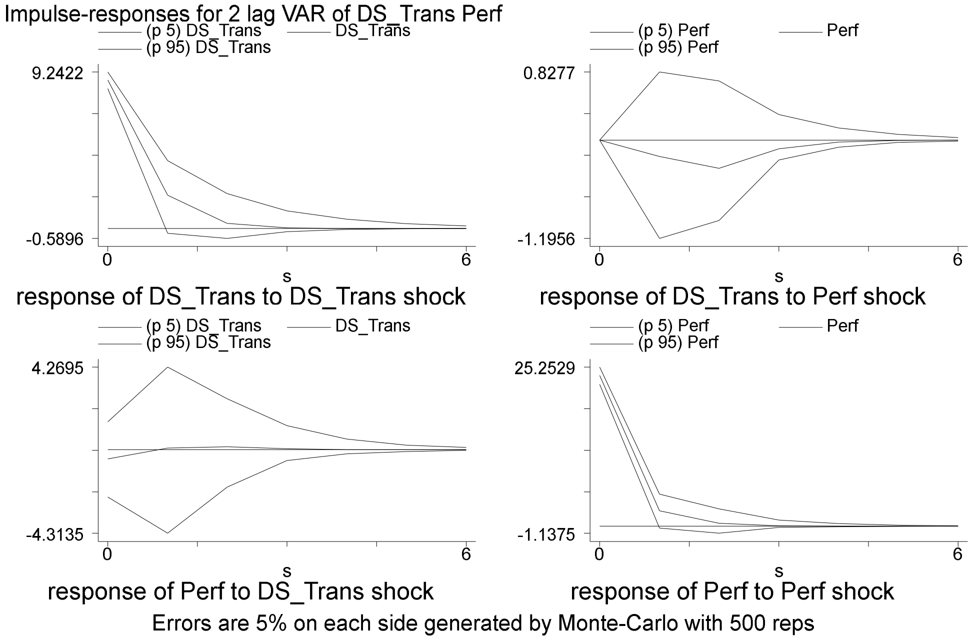

Figure 4. Impulse responses for private architects with "low" environmental performance (model of DS transformation and financial performance).

We first discuss general results for the sample of all private architects before proceeding to the ones with particular environmental performance. We observed that in the estimated coefficients and impulse responses, the financial performance's response to the DS transformation shock was positive. This was expected because research has shown that DS leads to higher customer satisfaction and more advanced revenue models. However, DS transformation had a negative response to financial performance shock, which implies that firms tend to maintain strategic stability over time when DS levels are as expected rather than continuing to increase. In this set of response results, we can observe that financial performance did respond consistently and positively to DS transformation shock, confirming Hypothesis 1a. The digital servitization transformation of private architects improves the sustainability of financial performance.

Observing the results for the "high" environmental performance private architects, we found that the financial performance's response to the DS transformation shock was still positive with a larger coefficient and had slower decay, suggesting that DS transformation is more effective for "high" environmental performance private architects, partially supporting Hypothesis 1b. In contrast to the general finding for the overall sample, the DS transformation's response to financial performance shock was also positive in the "high" environmental performance subgroup, indicating that "high" environmental performance firms will continue to increase their transformation efforts rather than implement strategic retention when faced with certain gains from DS. This implies that DS transformation and financial performance are intrinsically driven by each other in "high" environmental performance firms.

However, the results for the "low" environmental performance group were not promising. The financial performance's response to DS transformation shock was almost zero, indicating that for firms with "low" environmental performance, DS transformation has little to no effect on financial performance. The DS transformation's response to financial performance shock was negative, which indicates that private architects that do not benefit from DS transformation are gradually abandoning the strategy of DS transformation.

In order to compare the differences in the impulse response model results between our two samples (i.e., "high" and "low" environmental performance), we look at the differences in their coefficients. Since our two samples were independent, it is clear from current research that "the impulse responses of the differences are equal to the difference in impulse responses" (also applicable to modeling confidence intervals) [29] (p. 195). Our comparison showed that companies with a high environmental performance were better able to sustain benefits from digital service transformation and to further expand their strategies, whereas companies with a "low" environmental performance were less able to benefit and needed to scale down their strategies. Therefore, Hypothesis 1b was fully supported. Private architects with higher environmental performance are more effective at adopting digital servitization transformation.

4.2. Effects of Digital Infrastructure under Different Environmental Performance

With digital infrastructure as the shock variable and performance as the response variable, we implemented 500 Monte Carlo simulations for the shock and response variables at 95% confidence intervals to obtain the impulse response relationship graph. The horizontal axis is the response period, which represents the time axis of the impact mechanism; the vertical axis is the estimated coefficient, which represents the return of the impact mechanism; the upper and lower lines are the two bounds of the confidence interval; and the impulse response function point estimates are the curves in the middle of the figure. Figure 5 presents the graphs of impulse responses for the model with two variables (digital infrastructure support and financial performance sustainability) estimated for all samples. Figures 6 and 7 present the same model for the sample of firms with "high" environmental performance and the sample of firms with "low" environmental performance.

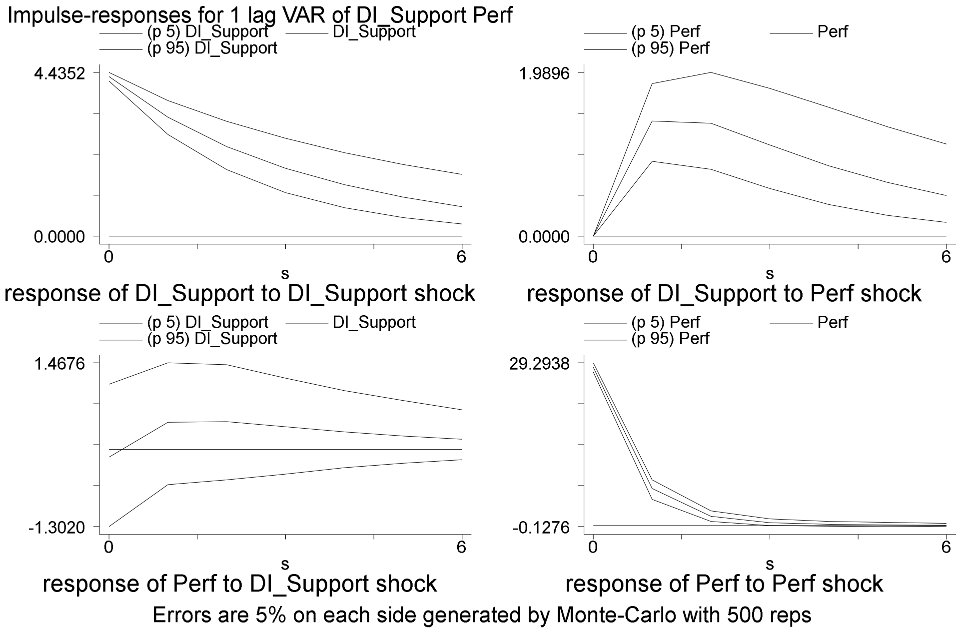

Figure 5. Impulse responses for the sample of all private architects (model of digital infrastructure support offered by public architects and financial performance of private architects).

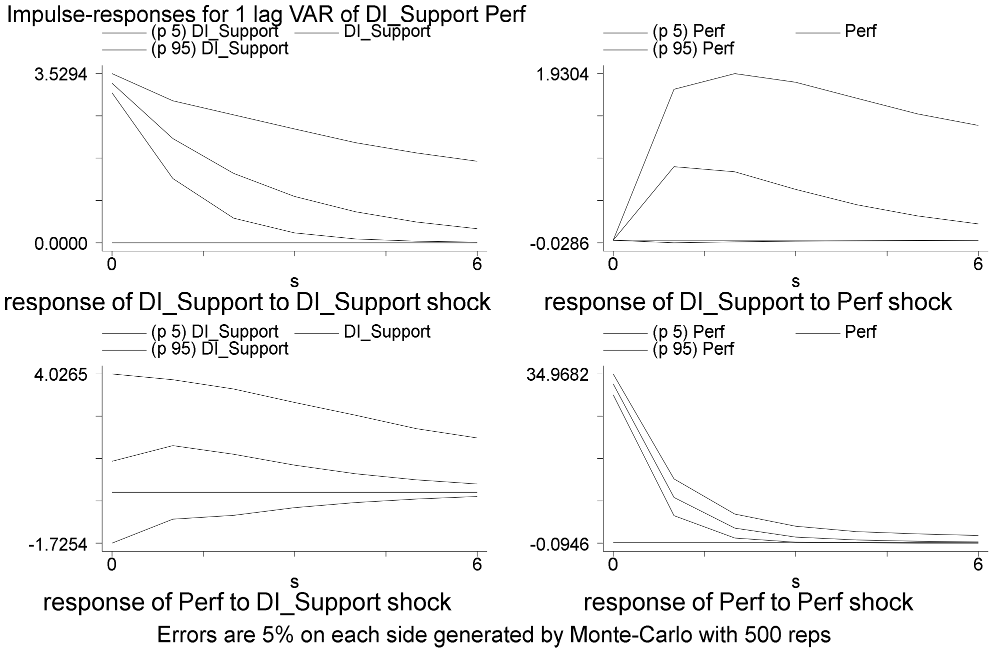

Figure 6. Impulse responses for private architects with "high" environmental performance (model of digital infrastructure support offered by public architects and financial performance of private architects).

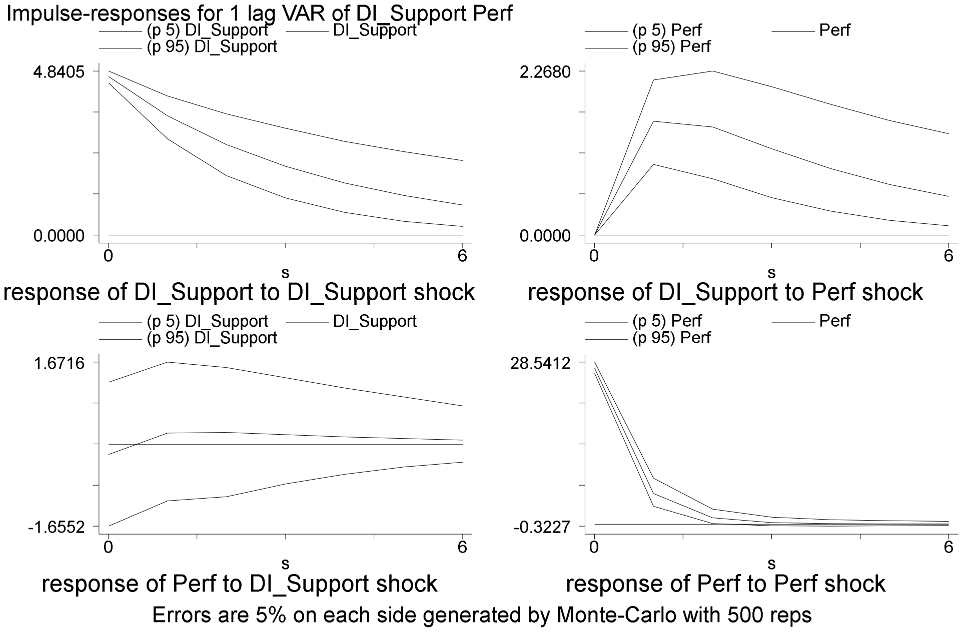

Figure 7. Impulse responses for private architects with "low" environmental performance (model of digital infrastructure support offered by public architects and financial performance of private architects).

As in the previous section, we firstly discuss the general results of the sample of all private architects and then proceed to the ones with particular environmental performance. We observed that the financial performance's response to digital infrastructure support shock was positive in the estimated coefficients and impulse responses. This was expected because digital infrastructure support provides local public architects with a larger digital platform and more potential users. However, this positive response was not obvious at the beginning of the period; there was a gradual revealing process, which implies that digital infrastructure support needs to take advantage of some accumulation. Digital infrastructure support responded positively to the financial performance shock, which implies that regions with higher financial performance have more incentive and ability to enhance local digital infrastructure support. In this set of response results, we can observe that private architects' financial performance did continue to respond positively to local public architects' digital infrastructure support shock. Therefore, Hypothesis 2a was supported. The digital infrastructure made by public architects improves the sustainability in the financial performance of local private architects.

Observing the results for the "high" environmental performance group, we found that the financial performance's response to the digital infrastructure support shock was still positive, with larger model coefficients and good performance at the beginning of the period. This suggests that "high" environmental performance private architects benefit more from public architects' digital infrastructure support. At the same time, the digital infrastructure support's response to financial performance shock was also positive in the environmental performance subgroup, which is consistent with the general findings.

Encouragingly, the results for the "low" environmental performance group were equally promising. The financial performance of private architects also responded positively to local public architects' digital infrastructure support shock, with similar results of insignificant effects at the beginning of the period in general and with a response coefficient that was only slightly lower than the coefficient for the "high" environmental performance subgroup. This implies that digital infrastructure support offered by public architects has a robust and positive effect on local private architects' financial performance, and both "high" and "low" environmental performance private architects are able to improve financial performance with digital infrastructure support. Therefore, Hypothesis 2b was partially supported. Private architects with higher environmental performance are more positively influenced by the digital infrastructure of public architects, while private architects with lower environmental performance also benefit from the digital infrastructure. In addition, financial performance improvement has a stronger incentive for local digital infrastructure construction, which is reflected in the response coefficient of digital infrastructure support on financial performance shock, which was larger in the "low" environmental performance subgroup results than in the "high" environmental subgroup results.

5. Discussion

We can conclusively state that in a digital ecosystem of private architects and public architects, both digital service transformation and digital infrastructure support enhance the financial performance component of sustainability, and that the environmental performance component of sustainability positively moderates this influence mechanism. This is reflected in "high" environmental performance companies, where the adoption of digital service transformation can lead to more financial performance improvement and a virtuous cycle of "financial performance improvement and expanded digital servitization transformation". The positive effects of this cycle have a longer decline cycle than other firms. However, low-performing companies' financial performance hardly improves in the process of digital servitization transformation, with a vicious cycle of "inefficiency-reduce digital service transformation". This can lead to a widening gap between firms with different environmental performances. Furthermore, digital infrastructure development can benefit different firms almost indiscriminately, although the effect is weak and slow compared to digital service transformation.

It has been suggested that companies encounter obstacles in digital transformation [2]; however, we have found a solution to this problem. We can confirm that digital ecosystems and sustainability have a mutually reinforcing relationship that facilitates DS transformation by building more effective digital ecosystems and motivating firms to improve their environmental performance. Current research has emphasized the role of digital servitization in ecosystems [73], and we enrich the theoretical framework of digital ecosystems by introducing the concept of digital infrastructure. The current research on the improvement of enterprise sustainable performance has been discussed from the perspective of digital technology and services [26,27,38]. We advance the research object of this issue to the strategic transformation of business models brought about by digital technology and service upgrading. The current study highlights the important role of digital ecosystems for sustainable development [14,20,68] and our findings allow the digital ecosystem and sustainability theory to move beyond a discussion of unidirectional facilitative influence mechanisms, and adds a two-way interaction between the two. In addition, we introduce the "ecosystem architect" framework of strategic management theory [28], and also focus on the heterogeneity among different architects to refine this theoretical system, confirming that the various dimensions of the financial and environmental performance of the sustainability concept have different relationships with the digital ecosystem, which enables the digital ecosystem and sustainability theory to be more focused. This allows the theory of sustainability to be applied to numerous real-world scenarios in a more focused manner, expanding the practical value of this theory.

Although the ISO14001 management system is applicable to all companies, this paper only selects manufacturing companies as a sample in order to control for industry heterogeneity. We look forward to investigating industries from other economic sectors in future studies to enrich the composition and characteristics of digital ecosystems.

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