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Case study

Digital Twin-Enabled Low-Carbon Business Model Innovation and ESG Outcomes: Evidence from Asian Manufacturing Cases

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Abstract: Digital twins are now used for more things than before, not only engineering design and maintenance. In many factories, it is being integrated with energy systems, product development tools, and supply chain platforms. However, a factory can be highly digital, yet its business model may remain largely unchanged. This paper examines this problem through three manufacturing cases in Asia: Haier interconnected washing-machine factory in Qingdao, Siemens Chengdu plant, and LG Smart Park in Changwon. Dynamic capabilities theory and natural-resource-based view are used to explain the cases. The analysis mainly looks at what information the twin provides, how managers use this information, what routines are changed, and whether the change affects customer value, delivery activities, or the way economic returns are captured. The three companies do not follow a single path. Haier put digital information into order-driven mass customization. Siemens connects factory and product twins with eco-design and internal testing of solutions. LG first builds flexible production, then some practices are copied to other plants, and later part of this capability is sold to outside customers. The strongest evidence concerns energy, carbon emissions, materials, and waste. Social and governance evidence is more uneven, as it depends heavily on work arrangements, data rules, and management. The cases show that a digital twin alone is not sufficient. It requires complementary investment, organizational change, and sufficiently reliable data; otherwise, low-carbon business model change and ESG outcomes are difficult to confirm. Also, better production efficiency does not always mean better ESG outcomes in the long term.

Keywords: digital twin; low-carbon business model innovation; ESG outcomes; dynamic capabilities; Asian manufacturing

1. Introduction

Manufacturers are now being asked to decarbonize far beyond the boundaries of the factory itself. Industrial internet platforms, sensors, cloud infrastructure, and digital twins more and more connect design, production, logistics, maintenance, product use, and recovery. Reducing energy use and direct emissions is still important, but companies are also expected to provide product-level carbon information, respond to greener customer preferences, satisfy supply chain disclosure requirements, and make ESG reports more credible when stakeholders examine them. These pressures are arriving at the same time that digital systems are spreading through manufacturing. As a result, digital upgrading and environmental improvement are often decided through the same operating choices instead of through two separate transformation programs [1,2].

The virtual model can then be used to simulate alternatives, anticipate failures, or feed information back into the physical system. This continuing data relationship distinguishes a digital twin from a static three-dimensional model or an occasional offline simulation[3,4], Digital twins are particularly important in this context because they link a physical object or process to a virtual representation that changes as new operating data arrive. In a low-carbon application, the same architecture can expose energy or material losses, test process settings before implementation, support preventive maintenance, and connect information generated during design, production, use, repair, and recovery.

A detailed virtual factory may improve diagnosis and control while leaving the firm's products, order processes, customer relationships, and revenue sources largely intact. This view is simplistic. The commercial consequences are harder to infer from the technology itself. Lower energy use per unit does not guarantee lower total energy demand when output rises quickly. Environmental performance can be equally ambiguous. The digital infrastructure also has its own resource requirements and introduces governance issues that ordinary process-improvement projects may not create, including cybersecurity exposure, ownership of operating data, worker monitoring, model error, and responsibility for automated recommendations[5]. It is useful to keep three questions separate: whether a twin has been adopted, whether the business model has changed, and whether the resulting changes support a believable improvement in ESG performance.

Existing research rarely brings these three questions together. Sustainable business model research begins from almost the opposite direction. Studies of digital twins provide detailed accounts of system architecture, simulation, manufacturing applications, and operation optimization, but they devote less attention to customer value, inter-firm arrangements, and the way firms capture returns [6,7]. It has established archetypes around resource efficiency, product stewardship, circularity, and functionality instead of ownership, yet the concrete role of a digital twin in moving a manufacturer toward those models is still less well documented [8,9]. Research linking digitalization with ESG performance adds a further difficulty because broad firm-level indicators can hide the organization route through which a specific technology is actually used. That makes it difficult to explain why similar digital investments produce different environmental, social, or governance outcomes across firms [10].

The three factories in this study provide a useful setting for examining that gap. Asian manufacturers are investing rapidly in digital systems while also coping with output growth, more complex production, tighter decarbonization requirements, and demand for a wider range of products. They differ in what the twin represents, the problem it is expected to solve, and the organizational level at which value eventually changes. Haier Qingdao, Siemens Chengdu, and LG Changwon are not treated here as three versions of the same digital transformation. The empirical question is narrower than whether digital twins are generally beneficial. It is how a twin moves from being an operating tool to becoming part of a low-carbon business model, and which ESG claims can reasonably be supported by the public evidence in each case.

Visibility, simulation, feedback, and lifecycle connectivity are treated not simply as technical features but as capabilities that may alter how decisions are made. Business model change is identified only when the resulting changes reach the customer proposition, the activity system, relationships with other organizations, or the way value is captured. That criterion allows the cases to be compared without assuming that every digital-twin project develops along the same path. This paper addresses these issues through a comparative analysis. It also prevents strong environmental metrics from being treated as a substitute for overall ESG performance. Governance enters the analysis twice: digitalization creates new requirements for data handling and automated decisions, while believable carbon claims also depend on the quality, traceability, and verification of the data used to produce them.

2. Literature Review and Analytical Framework

2.1. Digital Twin Concepts and Organizational Capabilities

For this issue, Kritzinger et al. [3] distinguish a digital model, a digital shadow, and a digital twin by the degree of data integration between the physical and digital sides. The term digital twin is used unevenly in both research and practice. A digital twin involves a stronger and more continuous connection that can include feedback. A digital model does not exchange data automatically, while a digital shadow mainly updates the digital object from the physical one. Jones et al. [4] similarly treat the twin as a system made up of a physical entity, virtual representation, data, services, and connections instead of as an isolated model. VanDerHorn and Mahadevan [11] emphasize another useful point: the representation should evolve with the physical system and its operating environment and should be built for a defined decision purpose.

On that basis, this study uses a relatively demanding definition. A one-off simulation, a static 3D representation, or a conventional dashboard is therefore not treated as a digital twin in the case analysis. A digital twin is a dynamic virtual representation of a physical object, production process, or integrated product-service system that remains connected to its real-world counterpart through recurring or high-frequency data exchange and is used to support decisions through simulation, prediction, or feedback.

From an organization point of view, the most useful question is not how advanced the twin is, but what decisions it changes. In one factory, the main gain may come from bringing equipment, product, energy, material, and process information into one operating view. A twin becomes more consequential when analysis is linked back to production control, quality, maintenance, or energy management instead of remaining an advisory display. Elsewhere, the greater benefit may be the chance to test a new design, maintenance rule, production schedule, or energy setting before making a physical change. At a broader level, it can also connect information across design, procurement, production, use, service, and recovery, making coordination possible across functions and locations [12,13]. These capacities create options for organizational change; they are not themselves evidence that such change has occurred.

2.2. The Boundary of Low-Carbon Business Model Change

Business model theory provides the reference point for deciding where that boundary lies. Foss and Saebi [14] reserve business model change for quite large alterations to one or more of these elements. For this point, The relevant issue is how the firm creates, delivers, and captures value, not how advanced its technology appears to be [15]. Improvements in cost, speed, or product quality may leave that underlying logic unchanged. A digital twin may make such alterations possible, but the innovation lies in the way products, activities, partnerships, or revenue arrangements are reorganized around the new capability rather than in the twin itself [16]. The same principle applies to sustainability: environmental or social improvements become part of a sustainable business model when they are built into core value-creating activities instead of treated as a separate compliance exercise [8].

Digital twins can enter that process at several points. They may support lower-energy or more repairable products, make environmental information visible to customers, reorganize internal and inter-firm coordination through real-time data, or make make-to-order production and lifecycle management more practical, In this paper, low-carbon business model change means a real change in the value offered to customers, the system through which value is created and delivered, or the working process through which value is captured, provided that the change contributes to lower lifecycle carbon emissions without making the business economically untenable. Once these capabilities mature, they may also support platform services, performance-linked arrangements, shared savings, or other ways of generating revenue.

If a twin identifies excessive electricity use on one machine and factory corrects the problem, the result is a useful low-carbon process improvement. Here the situation is different. The distinction is easiest to see in a simple example. The interpretation changes when the information from the twin begins to affect which orders are accepted and sequenced, how products are designed, how suppliers or customers participate, or how the firm earns returns from the capability. It does not automatically change the product, the customer relationship, the supplier network, or the revenue model.

2.3. Dynamic Capabilities and the Natural-Resource-Based View

Dynamic capabilities provide one explanation for the different results across factories. Teece [17] identifies sensing, seizing, and reconfiguring. A twin can help sensing because abnormal energy, machine problems, or demand changes become easier to see. Simulation may help managers choose a response. But the difficult part comes later. Information must change routines, decision rights, assets, or relationships. Otherwise, the twin remains mainly a technical tool. The natural-resource-based view looks at another side. Hart [18] discusses pollution prevention, product stewardship and sustainable development. Energy saving is close to the first one. Eco-design, repair and recovery are closer to product stewardship. When the data go outside one factory and support low-carbon service, the scope becomes wider. So the two theories are used together here, but they answer different questions.

3. Research Design

3.1. Method

A multiple case study is suitable here because a digital twin is not an isolated intervention. In the factories examined here, it sits inside a wider production and sustainability system, and the issue of interest is the sequence through which technology, decisions, and organizational arrangements interact. Case research is useful for process questions of this kind and for theory development where causal boundaries are still being clarified [18,19]. The aim is not to estimate an average treatment effect.

3.2. Case Selection

Each case illuminates a different part of that boundary. Haier Qingdao shows how customer orders can be linked with materials, production, and delivery in a mass-customization setting. Siemens Chengdu combines a factory twin with product-level digital representations, making it possible to follow a progression from internal decarbonization toward eco-design and solution development. LG Changwon places more weight on flexible manufacturing. The appliance plant continues to earn most of its revenue from product sales, but the manufacturing knowledge built at Smart Park was later transferred in LG and offered externally through B2B smart-factory services. The cases vary not just in their technical configuration but also in the organizational level at which new value appears. (See Table 1)

Table 1. Case Characteristics and Business Model Change

Case	Location	Digital Twin Object	Main Transformation Problem	Business Model Change

Case	Location	Digital Twin Object	Main Transformation Problem	Business Model Change
Haier interconnected washing-machine factory	Qingdao, China	Production lines, worker operations, orders, and manufacturing processes	Small batches, product variety, fast delivery, and low-carbon production	Order-driven mass customization with substantial change in value proposition and delivery
Siemens factory	Chengdu, China	Factory, products, and connected design, production, and procurement data	Decarbonization during expansion, eco-design, and product carbon information	Eco-design, Customer Zero, and solution incubation with platform features
LG Smart Park	Changwon, South Korea	Factory, assembly lines, and material transport	Multi-model flexible manufacturing, quality, physical workload, and energy efficiency	Flexible manufacturing, network replication, and B2B solutions

Note: Compiled according to references [21-27]

4. Case Analysis

4.1. Haier Qingdao: Order-Driven Mass Customization and Low-Carbon Coordination

Haier Qingdao faces a practical problem: more product types, smaller batches, and customers wanting faster delivery. A forecast system makes this harder because the factory may produce before real demand is clear. Haier therefore gives actual orders a bigger role. Orders link with procurement, production, and logistics. It is not a very complicated idea. But many units must see and use the same information [21,22].

The twin is only one part in this system. Public materials indicate that shop-floor activities are mapped and abnormal information can be sent to an intelligent diagnosis platform. Workers then adjust the line. Reported employee efficiency improvement is about 35%. Digital ordering, supply-chain algorithms, positioning, and automated equipment work alongside the twin. Here, the twin mainly helps to visualize the factory and find problems faster.The business model point comes from order fulfillment, not from thetwin itself. Haier reports that 85% of finished products do not stay in a conventional warehouse for long, and the end-to-end digital order system increases production efficiency by more than 20%. The factory can change between variants in smaller batches. Suppliers and logistics also follow the order data. Customer orders enter production more directly. This is the bigger change.

Low-carbon results come from another group of actions. Energy consumption is reported to be about 20% lower than in a traditional factory, while carbon emissions are about 30% lower. Digital energy management matters here, as does renewable electricity. The industrial park also has a 10 MW photovoltaic installation. It generates roughly 10 million kWh each year, around one quarter of the factory's electricity demand. So the number should not be read as a pure effect of digital twin.The social and governance evidence is thinner. Faster diagnosis may make some work easier, but detailed operating data can also include worker movement and behavior. Who can see these data? Whether it enters performance evaluation is not clear from public materials. The same issue exists for order, machine, and energy data. More traceability helps operations, but data-use rules become more important too.

Qingdao is better understood as several changes working together. The twin maps and diagnoses the shop floor. Order data changes production and delivery. Energy management and photovoltaic power relate more directly to carbon results. These parts are connected, butthey are not the same thing. The available evidence does not, however, justify attributing all environmental gains to the twin or making strong claims about worker outcomes that were not directly measured..

4.2. Siemens Chengdu Factory: Eco-Design, Carbon Information, and Solution Incubation

It produces SIMATIC industrial automation products and has developed extensive vertical and horizontal data integration. Hundreds of physical and virtual sensors collect information from products, processes, and factory systems, creating the data base for a comprehensive digital representation of the plant. Siemens' Chengdu plant presents a different arrangement. As output expanded, the problem shifted from visibility alone to whether energy use, waste, and value-chain emissions could be prevented from rising in step with production. The twin was used together with digital energy management, predictive maintenance, waste-reduction measures, and product eco-design [23].

At the plant level, continuous energy data are used to identify abnormal consumption, while equipment data support maintenance before failures create downtime or inefficient operating conditions. Environmental considerations can thus enter before a design is fixed. The product side reaches further upstream. Siemens NX is used to create product twins, and Teamcenter links information across product development, production engineering, and procurement. Public materials mention changes to printed circuit boards, lower or substituted plastic use, and recyclable packaging. Digital nameplates on some products also provide lifecycle, repair, and recycling information through QR codes. Here the digital representation does more than mirror the current factory. it becomes part of decisions about product composition and the information carried forward with the product.

Design makes the Siemens case go further than factory control alone. Product function and quality are still important, but material use, repair, recycling and carbon information also enter the product side. This requires design, procurement, production, and suppliers to work together. Siemens also uses the 'Customer Zero' idea. Some solutions for customers are first tried in its own factory. Chengdu is thus a production site, but also a testing ground for a later solution business.

Siemens reports a large change in Chengdu: production output increased by 92% from 2019, while absolute greenhouse gas emissions fell by 93%. The reported improvement is quite large, but the figures describe the combined program instead of the effect of one technology. World Economic Forum materials report a 24% reduction in energy use per unit of product and a 48% reduction in production waste [22]. In fiscal 2023, greenhouse gas emissions per unit of production were 97% below the relevant baseline. Siemens also associates design optimization and reusable packaging with about 3,000 tonnes of CO_2-equivalent Scope 3 reductions in fiscal 2022. These results emerged alongside digital energy management, predictive maintenance, AI-enabled waste management, packaging changes, eco-design, and carbon-information systems and should be read as outcomes of the wider transformation.

Among the three cases, Chengdu offers the broadest set of environmental indicators. Public materials are much less specific about the social dimension, and the evidence covers absolute greenhouse gas emissions, energy intensity, production waste, and resource efficiency across parts of the product lifecycle. They show that product development, production, and procurement have to work more closely together and that digitalized production and eco-design require new skills, but they do not provide a comparable set of indicators on training, employment quality, or employee experience. The social claims made from this case are therefore deliberately limited.

Governance is more visible because the plant's sustainability model depends heavily on carbon information. SiGREEN, product carbon footprint tools, and digital nameplates increase the availability and traceability of product- and supply-chain data. Yet more granular data do not automatically produce more accurate accounting. They can also bring information from several supply-chain actors into a more continuous carbon-management process. Results still depend on the boundary chosen for the calculation, the quality of supplier inputs, the verification method, access controls, and assumptions embedded in the model. Digitalization can make carbon information easier to trace, but it simultaneously raises the standard required for data governance and for assigning responsibility when data or models are wrong.

The earliest contribution is operation through visibility, energy management, and maintenance. Product twins then move material and environmental considerations into design. Chengdu shows how a factory twin can become connected to a wider process of value creation. The Customer Zero model gives the plant an additional role as a place where solutions are tested and refined before they are offered to outside customers. Knowledge generated inside the factory is valuable not just because it reduces internal costs but also because it can feed Siemens' external solution-development activities. The case thus sits between operational decarbonization, product stewardship, and the incubation of marketable digital and low-carbon services.

4.3. LG Changwon Smart Park: Flexible Manufacturing, Employee Workload Reduction, and the Commercialization of Manufacturing Capabilities

LG Changwon Smart Park begins with another manufacturing challenge. The plant needed to handle an increasing variety of appliance models without allowing material-flow complexity or quality problems to disrupt production, and LG expanded an earlier assembly-line visualization system into a digital twin that receives production data continuously. The focus is on the responsiveness of the overall production system rather than a single machine or product. The virtual factory is refreshed about every 30 seconds and is used to assess current production, anticipate disruption, and coordinate the supply of parts and materials as logistics conditions change [24,25].

Production and material flows can be examined virtually before changes are made on the shop floor, allowing potential congestion, equipment problems, or logistics bottlenecks to be identified earlier. The twin also works with 3D logistics, edge computing, machine learning and automated equipment. Public sources report warehouse space fell around 30% and material-transport time about 25%. The same system can handle more model combinations. Robots also take over some repeated heavy work, including refrigerator doors of about 20-22 kilograms. This is one social effect that is quite direct.

LG reports several numbers together. From 2020 to 2021, output per hour rose about 17%, while cost of defective-product returns fell around 70%. Unit energy input and greenhouse gas emissions both fell about 30% [25]. World Economic Forum later reported a similar energy change [26]. But twin, automation, logistics, machine learning and energy management were used together. It is not possible to attribute the 30% solely to the twin.

Smart Park also produced know-how, not only appliances. Some routines and data methods were standardized and could be copied to other plants. The plant then became a reference site in LG. This goes beyond a single factory efficiency project. In 2022, LG announced plans to extend technologies validated at Smart Park to 26 production sites in 13 countries by 2025.

Smart Park still captures most of its value by making and selling physical appliances, and public evidence does not show that customers pay a distinct premium because the products come from a lower-carbon factory. A value-capture change appears later and at the firm level. This network effect is different from a new revenue model in the appliance plant itself. In 2024, LG created a Smart Factory Business Division and began offering B2B customers services that include digital twins, production planning, factory design and construction, operation optimization, and continuous-improvement consulting [27]. Manufacturing knowledge developed for internal use was thus turned into an external commercial offering.

The ESG evidence from Smart Park is mixed in both type and strength. Governance becomes important because high-frequency production data are linked to machine learning and automated equipment. Environmental evidence mainly comprises unit energy and unit greenhouse gas emissions. One social point is also clear: some repeated heavy lifting is replaced by robots. Other labor effects are not reported much. Regarding governance, model checking, cybersecurity, emergency stops, and human responsibility become practical issues. When LG copies the system to other countries, labor rules, safety rules, and data rules can differ.

5. Cross-Case Analysis

The cases also show why there is no single digital-twin business model. Haier begins with demand and uses order information to coordinate smaller-batch customized production and delivery, and Siemens pushes environmental information upstream into product design and uses its own factory to test solutions intended for customers. Similar digital architectures can thus support quite different routes of value creation. LG begins with factory flexibility, standardizes the resulting manufacturing knowledge for use across the network, and later develops an external smart-factory business around part of that capability.

Every case includes internal process change, but process change alone is not enough to establish a new business model. How deep the innovation appears depends partly on where the organizational boundary is drawn. At Siemens, it reaches eco-design and solution development for external markets. At Haier, the digital system reaches customer orders and the organization of delivery. At LG, the Changwon appliance plant is still largely in a product-sales model, while later commercialization of Smart Park capabilities changes the way economic returns are captured at the corporate level. Treating all three cases as equally deep business model changes would obscure where the new value is actually created and captured. (See Table 2）

Table 2. Cross-Case Comparison

Dimension	Haier Qingdao	Siemens Chengdu	LG Changwon
Main path	Order-driven mass customization	Eco-design and solution incubation	Flexible manufacturing, cross-site replication, and capability commercialization
Main digital twin object	Production operations, lines, and order processes	Factory, products, and lifecycle data	Assembly lines, logistics, and factory systems

Dimension	Haier Qingdao	Siemens Chengdu	LG Changwon
Value proposition	Faster customized delivery	Low-carbon, traceable, repairable, and recyclable products	Faster multi-model response with energy and quality improvement
Value creation and delivery	Make-to-order procurement, production, and logistics	Coordination across design, procurement, production, and suppliers	Flexible production, three-dimensional logistics, network replication, and external solution development
Value capture	Higher order value and platform coordination; limited project-level revenue evidence	Internal savings linked with external digital and low-carbon solutions	Product sales dominate at factory level; B2B smart-factory solutions extend firm-level value capture
Depth of business model innovation	Relatively deep	Moderate to deep	Moderate; deeper when firm-level commercialization is included
Main environmental evidence	Energy, emissions, photovoltaics, and inventory-reduction potential	Absolute emissions, unit energy, waste, and Scope 3	Unit energy efficiency and greenhouse gas emissions
Main social and governance issues	Worker efficiency, operational data, and algorithmic management	Cross-functional coordination, carbon-data verification, and supplier-data governance	Worker relief, model safety, and cross-national data governance

6. Discussion

6.1. Low-Carbon Value Arises through Organizational Change of Arrangement

The main finding is about organization rather than just technology. A twin can show a factory very clearly, but this alone changes nothing. Low-carbon results appear when people use the information to change orders, design, maintenance, energy, or material flows. In all three cases, several things are mixed together:the twin, other digital tools, equipment, cleaner energy, and management. The independent effect of the twin cannot be separated from public evidence.This also changes what future research should measure. Adoption yes or no is too simple. Researchers can ask what object is twinned, how often data moves, whether the model output enters a real decision, and which routine actually changes. Complementary assets also matter. This interpretation is consistent with work on digital and sustainable business model complementarities [2], but the cases here cannot provide a clean causal estimate.

6.2. A Continuum from Operational to Business Model Change

The cases look more like a continuum. At one end, the twin improves one machine or one energy task and the business logic is almost the same. A deeper step is cross-function change. Stronger business model change requires customer value, inter-firm relationships, or value capture to move as well. LG shows this quite clearly because factory change comes first, while the later smart-factory business changes how money is earned. Haier and Siemens go further through order logic, eco-design, and external solutions.This continuum avoids two easy overstatements. Large energy savings do not automatically mean business model innovation. A new digital service also does not automatically mean low carbon. Both require evidence. If business value arrangements change and environmental results can also be seen, the claim is stronger. If only one side changes, the label should be used more carefully.

6.3. Features of the Asian Manufacturing Context

Asian manufacturing has a special background in these cases. Output is still growing, product types are increasing, and delivery times are getting shorter. Decarbonization happens during this pressure, not after it. Environmental changes may be seen sooner because meters and shop-floor systems already record them. Work arrangements and governance can move more slowly. The factories are also being used as places where technology is tested and know-how is transferred through organizations, not simply as sites of assembly.

Make-to-order production, eco-design, supply-chain carbon information, and the transfer of manufacturing knowledge can all change how value is created and delivered even when physical products still are central to the business. The limits are equally important. The cases also show that low-carbon business model change in Asian manufacturing need not follow a Western servitization template. A highly efficient digital factory can still experience rising absolute emissions, disputes over worker data, or unclear responsibility for model-based decisions if carbon accounting, employee participation, and digital governance still are weak.

6.4. Theoretical Contributions

The theoretical contribution can be understood as several connected differences. It then separates capability from business model change: those capabilities become relevant to business model change only when they alter the value offered to customers, the activity system, inter-organizational relationships, or the way economic returns are captured. The study links recurring digital-twin capabilities - visibility and traceability, virtual experimentation, feedback into operations, and lifecycle coordination - with the sensing, seizing, and reconfiguring processes of dynamic capabilities theory. The cross-case comparison identifies three routes through which this can occur: order-driven mass customization, eco-design combined with solution incubation, and flexible manufacturing followed by replication and commercialization. Governance is part of the same explanation because data quality, verification, access rights, and model responsibility are both requirements for believable environmental claims and obligations created by the digital system itself.

7. Managerial and Policy Implications

7.1. Managerial Implications

Managers are likely to obtain more value by beginning with a concrete operating problem instead of with the label 'digital twin.' Inventory mismatch requires connections among demand, scheduling, production, and logistics. These are different projects, not interchangeable applications. A product carbon footprint problem requires reliable product and supply-chain data. Excessive facility energy use requires metering that can locate where losses occur. Each implies a different boundary for the twin, a different set of organizational participants, and a different package of complementary investments.

Firms need a defensible baseline for absolute energy use or emissions, unit intensity, output, and product mix if later changes are to be interpreted in a believable way. Without such a baseline, a digital project may generate more information without making attribution any easier, Measurement should be prepared before implementation, not reconstructed after the project is finished. External reporting should also state clearly when an outcome reflects a portfolio of photovoltaic power, equipment upgrades, process redesign, and digital technologies instead of presenting the entire result as the effect of the twin.

Factory data may make make-to-order production workable; product twins can support eco-design and more detailed carbon information; and a mature internal application may later become a platform or external solution. The surrounding business model deserves the same attention. These developments represent different forms and locations of value creation. If the customer proposition, key activities, partner relationships, and the way value is captured are essentially unchanged, the more accurate description is operation innovation instead of business model change.

Also, digital governance should be designed together with the technical system. Worker-operating data and supplier carbon data are especially sensitive because they cross organization or personal boundaries. Data ownership and quality standards, access controls, cybersecurity, model validation, human review, and responsibility for decisions are not issues that can be added after deployment. In those settings, informed participation, data minimization, dispute-resolution procedures, and independent assurance may be as important as model accuracy.

7.2. Green Finance and Public Policy

Project-, equipment-, and product-level energy or carbon data can give lenders a more frequent view of performance than annual self-reported summaries. Where accounting boundaries are defined, the model is validated, and the underlying data are independently assured, financial institutions may be able to detect departures from sustainability-linked targets earlier and assess some forms of transition investment with greater precision. Digital twins may also improve the information available to green and transition finance.

The existence of a digital twin should not, however, be treated as evidence that an activity is green. Lenders still need to ask whether the project delivers measurable reductions in absolute emissions, resource use, or lifecycle impact and whether output growth, purchased electricity, and supply-chain emissions have been taken into account. Twin-generated data can strengthen monitoring and verification, but they do not replace green taxonomies, carbon accounting rules, or external assurance.

Common data interfaces, carbon accounting boundaries, and verification rules could be developed for sectors such as home appliances, industrial equipment, chemicals, and industrial-park energy systems. Such arrangements would make low-carbon operating data more usable for lenders while still requiring protection of commercially sensitive information. There is also a regional policy role where manufacturers share common supply chains or industrial infrastructure. Shared test environments, green-upgrading finance, and third-party digital services may be especially useful for smaller firms that cannot build the same infrastructure as large lighthouse factories, reducing the risk that the combined digital and green transition widens existing capability gaps.

8. Conclusion and Limitations

This study asks a narrower question than whether digital twins are generally useful: when do they become part of low-carbon business model change? At Haier, digital information is built into an order-driven production and delivery system, and The three cases suggest that the answer depends on what happens after the technology begins to generate information. At Siemens, it reaches product design and the internal testing of solutions. At LG, it supports flexible manufacturing, is standardized for replication across plants, and later contributes to an external smart-factory business. The cases differ not just in technical application but also in the organizational level at which new value is created and captured.

Environmental evidence is much more developed than social or governance evidence in all three cases. Energy, emissions, waste, materials, and equipment performance are close to the systems being measured and can often be reported numerically. Nor should the technology be assumed to be inherently green. Worker monitoring, skill requirements, cybersecurity, data rights, and responsibility for model-based decisions are less visible in public materials, but they are not less consequential. Output rebound and the energy and material requirements of digital infrastructure can offset part of an efficiency gain. A convincing assessment so needs to consider business model change, the environmental result, and the safeguards surrounding people, data, and automated decisions together.

The analysis is based on public documents instead of interviews, internal records, or direct observation. Most numerical indicators come from company materials or lighthouse disclosures, and the sources do not provide a common measurement basis, independent assurance for every metric, or a counterfactual against which the results can be estimated. The evidence also means the conclusions cannot be generalized too far. The selected firms are also large, technologically mature manufacturers. Smaller firms may face very different constraints in data, investment, and organization capability. Most importantly, the case design can reconstruct a plausible organizational process, but it cannot identify the independent causal effect of a digital twin on ESG performance.

Future research could test the proposed process with evidence that is closer to organizational decision-making. In China, this issue is particularly important for measurement, reporting, and verification: high-frequency project and product data may improve monitoring only if confidential commercial information can be protected and responsibility for the underlying carbon calculations still is clear. Interviews and longitudinal records could follow changes in decision rights, contracts, customer participation, and revenue arrangements before and after a twin is introduced, while environmental data could compare movements in absolute emissions with movements in intensity. Another useful question is whether green finance changes firms' ability to convert digital information into broader low-carbon organizational change.

Author Contributions

The author independently completed the conceptualization, source collection, case analysis, and writing of the study.

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Institutional Review Board Statement

Not applicable. The study uses publicly available documents and does not involve human participants or animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

The case evidence is drawn from publicly available publications, corporate websites, and institutional reports identified in the references. The study did not generate new survey or experimental data.

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Conflicts of Interest

The author declares no conflict of interest.

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