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From Industry 4.0 Readiness to Sustainable Manufacturing: An IMPULS-Informed PLS-SEM Analysis of Organisational and Technological Capabilities

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Abstract

The transition towards Industry 4.0 has significantly heightened the need for manufacturing firms to assess their organisational readiness for the digital transformation of production systems while aligning with sustainable manufacturing goals. Despite increasing scholarly attention to Industry 4.0, there is limited evidence of how organisational and technological capabilities, through readiness, translate into sustainable manufacturing outcomes in emerging economies such as Pakistan. This study addresses this gap by examining the relationships among the six IMPULS dimensions, namely strategy and organisation, smart factory, smart operations, smart product, data-driven services, and employees, together with additional organisational and technological readiness factors, Industry 4.0 readiness, and sustainable manufacturing in the context of Pakistani manufacturing firms. A quantitative cross-sectional design was used, while data were collected from 470 respondents across various manufacturing sectors using a structured questionnaire constructed on validated measurement scales. This study develops and empirically tests an extended IMPULS-informed readiness-to-sustainability framework that integrates established Industry 4.0 readiness dimensions with additional organisational and technological capability factors relevant to sustainable manufacturing. The study makes a methodological distinction by operationalising an IMPULS-informed framework that connects its six dimensions with Industry 4.0 readiness and sustainable manufacturing within a single empirical model. The proposed model was examined using partial least squares structural equation modelling (PLS-SEM). The findings reveal that strategy and organisation, employees, smart products, and smart operations substantially contribute to Industry 4.0 readiness. Conversely, smart factories and data-driven services do not have a significant direct impact on readiness. Sustainable manufacturing is strongly influenced by Industry 4.0 readiness, smart operations, and the smart factory. Mediation analysis further indicates that Industry 4.0 readiness serves as a significant transmission mechanism linking strategy and organisation, employees, smart products, and smart operations to sustainable manufacturing. The study extends the IMPULS framework by validating its relevance in an emerging economy and by demonstrating that sustainability gains from digital transformation rely more on coordinated organisational and operational readiness than on isolated technology adoption. The results provide evidence-based prioritisation guidance for managers and policymakers seeking to prioritise strategic alignment, workforce skills, and operational integration for successful, sustainable industrial transformation.

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1. Introduction

Industry 4.0 represents the integration of cyber-physical systems, IoT, big data analytics, and smart automation in manufacturing [1]. While Pakistan's manufacturing sector remains a cornerstone of economic growth, its readiness for Industry 4.0 transformation remains under-assessed. This study adopts the IMPULS Readiness Framework, developed by VDMA & Acatech (Germany), customised with validated academic sources to suit the Pakistani context. Industrial revolutions have led to significant shifts in the technological landscape [2]. The implementation of Industry 4.0 technologies can offer significant benefits to the manufacturing value chain. These gains include, but are not limited to, enhanced productivity and efficiency, increased sharing of knowledge and teamwork, greater flexibility and agility, simpler compliance with regulations, a better customer experience, lower costs, and higher revenues [3]. The readiness model of Industry 4.0 is described as the "degree to which organisations can take advantage of Industry 4.0 technologies" [4].

There are many Industry 4.0 readiness models developed in both the practitioner and academic literature [5]. Firms increasingly acknowledge that, to remain competitive, environmental and social considerations need to be integrated into their core business strategies. The IMPULS framework is used to assess an organisation's readiness for Industry 4.0, particularly in the context of digital transformation [6]. It helps companies to evaluate their current states and identify areas for improvement in six key dimensions: strategy and organisation, smart factories, smart operations, smart products, data-driven services, and employees. The framework provides a structured approach to understanding an organisation's digital maturity and to guiding its Industry 4.0 implementation efforts [7].

This research evaluates the current state of Industry 4.0 readiness among manufacturing firms in Pakistan using the internationally recognised IMPULS framework and identifies key factors and barriers affecting digital transformation. In parallel, structured implementation roadmaps are important because manufacturing firms often struggle to translate Industry 4.0 technologies into coordinated operational transformation, particularly when digital initiatives are introduced without clear sequencing, workforce preparation, or process alignment [8]. Technological readiness has been extended across a variety of dimensions through advancements in enabling technologies, including the Internet of Things (IoT), cloud computing, autonomous robots, cyber-physical systems, augmented reality, and artificial intelligence [9]. Enhancing this digital readiness, where employees are ready and willing to use such technologies, is critical to a successful digital transformation [10]. An organisation exhibits organisational readiness by sharing resources, developing IT infrastructure, and hiring staff with crucial business analytics skills [11].

Although the literature on Industry 4.0 and sustainability already exists, there are still key gaps in research. The previous literature has focused mainly on certain aspects of Industry 4.0 (e.g., smart factories and data analytics), without introducing an integrated, comprehensive framework that addresses both organisational (strategy and organisation) and technological (smart operations, smart products, data-driven services, and employees) dimensions [12]. The traditional models, such as the IMPULS framework, are not fully applicable in the context of Pakistan, especially in terms of language, sectoral relevance, and existing digital capabilities. This paper fills this gap by validating a future model, an attempt to provide a practical and inclusive tool for assessing Industry 4.0 readiness.

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According to [13], the main reason that most industries are not adopting Industry 4.0 is a lack of knowledge or expertise in assessing their organisational readiness. The lack of readiness may result in firms not using Industry 4.0 technologies to their full potential, which will interfere with their operations and minimise the impacts of sustainability [14]. The existing research is inadequate to explain how other organisational and technological factors, namely strategy and organisation, smart factories, smart operations, smart products, data-driven services, and employee capabilities, interact to influence the process of creating sustainable manufacturing [15].

The integration of digital transformation with sustainability objectives in contemporary manufacturing systems is gaining increasing importance, which motivated the present study [16]. Firstly, this study proposes a holistic and integrated multidimensional model of Industry 4.0 by linking strategy and organisation, smart factories, smart operations, smart products, data-driven services, and employees to sustainable manufacturing. Second, it introduces Industry 4.0 readiness as a mediating construct, thereby offering new insights into how organisational and technological capabilities are converted into sustainability outcomes. From a practical and managerial perspective, the study is timely because manufacturing firms in developing countries are under increasing pressure to improve productivity, reduce resource waste, strengthen supply chain resilience, and comply with sustainability expectations while avoiding fragmented digital investments [17]. The proposed model, therefore, provides managers with a structured basis for prioritising readiness building, workforce capabilities, operational integration, and technology alignment before expecting measurable sustainability gains from Industry 4.0 transformation [18,19].

Although the wider project is positioned within international digital manufacturing capacity building, the empirical component of this article focuses specifically on Pakistan's manufacturing sector. The study therefore examines how the IMPULS dimensions, together with additional organisational and technological readiness factors, shape Industry 4.0 readiness and sustainable manufacturing within Pakistan's emerging industrial context, where digital transformation remains uneven across firms, sectors, regions, and ownership structures. To the best of the authors' knowledge, this is one of the first empirical studies to develop and test an extended IMPULS-informed readiness-to-sustainability framework within Pakistani manufacturing firms, offering a more comprehensive explanation of how readiness capabilities translate into sustainable manufacturing outcomes.

2. Literature Review

Guided by the proposed IMPULS-informed framework, this study develops hypotheses that link its six functional dimensions—strategy and organisation, smart factories, smart operations, smart products, data-driven services, and employees—with Industry 4.0 readiness and sustainable manufacturing. The framework assumes that these dimensions represent interrelated organisational, technological, operational, product, data service, and human capability domains. Industry 4.0 readiness is positioned as the mediating mechanism through which these capabilities are expected to translate into sustainable manufacturing outcomes [20]. The following review therefore establishes the conceptual and empirical justification for the direct effects of the IMPULS dimensions and their indirect effects through Industry 4.0 readiness.

2.1. Relationship Between Strategy and Organisation and Industry 4.0 Readiness

Industry readiness serves as an external alignment process because it requires a proper connection between the change initiative and market conditions, regulatory requirements, and technological advancements. The transformation of organisations to digital form is commonly known as Industry 4.0 [21]. It completely changes the ways in which an organisation operates. All functions of an organisation undergo a change, e.g., from manufacturing to all other activities that take place within and external to the industry changes [15]. Strategy and organisational structure are foundational enablers for firms aspiring to transition into Industry 4.0 environments. Ref. [22] proposed that companies with a well-defined Industry 4.0 strategy and clear leadership visualisation are better equipped to evaluate, plan, and implement digital transformation pursuits. Their Industry 4.0 Maturity Index accentuates strategy and leadership as key factors enabling readiness, emphasising that managerial skills are strongly shaped by strategic clarity and organisational goals. Additionally, ref. [23] asserted that senior leadership's readiness improves significantly when the organisational structure encourages innovation, cross-functional teamwork, and agile decision processes.

Hypothesis 1: *Strategy and organisation significantly impact Industry 4.0 readiness.*

2.2. Strategy and Organisation and Sustainable Manufacturing

Sustainable manufacturing involves integrating processes and systems capable of producing high-quality products and services while using fewer and more sustainable resources, such as energy and materials [24]. It prioritises employee, customer, and local community safety and aims to reduce environmental and social impacts throughout the product's lifecycle [25]. The association between strategy and sustainable manufacturing has gained increased interest in recent studies. Although earlier research saw sustainability efforts as a financial strain, recent work emphasises their importance in improving a company's competitiveness and long-term performance. Ref. [26] notes that aligning strategies with sustainability helps firms to optimise resource utilisation, lower environmental impacts, and enhance stakeholder value. Nonetheless, the financial gains of sustainability initiatives depend on the context, since not all innovations yield prompt economic returns. This highlights the need for strategic planning and strong organisational support to effectively implement sustainable manufacturing practices [27].

Hypothesis 2: *Strategy and organisation significantly impact sustainable manufacturing.*

2.3. Relationship Between Smart Factory and Industry 4.0 Readiness

The introduction of smart factory technologies has a significant positive impact on the preparation for Industry 4.0 by increasing the transparency of data, the flexibility of operations, and the decentralisation of decision-making [28]. Nonetheless, there are still obstacles, especially for SMEs, which, in most cases, lack the resources and structures to assess their levels of readiness [2]. From an economic perspective, smart factories have a direct impact on production, services, and final products [29]. The innovative production control systems that accompany Industry 4.0 ensure increased product transparency by multiplying data and enabling real-time capabilities, so that the resulting rapidly rising data volume will intensify decentralised decision-making [30]. Many businesses understand the potential of digital transformation, but they frequently find it difficult to evaluate their levels of Industry 4.0 readiness, which makes it essential to put strategic changes into practice [31]. Without a defined plan, companies may invest in Industry 4.0 technologies without fully understanding their impacts, which could lead to suboptimal outcomes and ineffective results.

Hypothesis 3: *Smart factories significantly impact Industry 4.0 readiness.*

2.4. Relationship Between Smart Factory and Sustainable Manufacturing

I4.0 involves the adoption of front-end technologies, with smart manufacturing playing a key role [32]. By leveraging real-time analytics, automation, and resource optimisation techniques, organisations can reduce waste, enhance energy efficiency, and minimise environmental impacts. The concept of the smart factory involves the use of smart devices, such as smart machines, robots, and workpieces, that communicate continuously throughout the production process [33]. In addition, smart production ensures customer satisfaction by producing high-quality products, custom designs, and short production lead times [25]. In other words, Industry 4.0 aims to create the seamless integration of processes within a smart, cyber-physical factory. Four subjects are proposed as Industry 4.0 key components: CPS, IoT, IoS, and the smart factory (SF). From these key components, six principal designs were derived [34]. The benefits of sustainable manufacturing include cost reduction through resource efficiency and improved regulatory compliance, better brand reputation, new market access, reduced labour turnover by creating attractive workplaces, and a long-term business approach by creating opportunities to access financing and capital [35].

Hypothesis 4: *Smart factories significantly impact sustainable manufacturing*.

2.5. Relationship Between Smart Operations and Industry 4.0 Readiness

The integration of smart operational systems significantly contributes to Industry 4.0 readiness by improving data accuracy, forecasting capabilities, and system interoperability. For instance, the integration of ERP with IoT and big data analytics allows organisations to improve their operational visibility and efficiency [36]. The advanced ICT used in smart operations includes ERP systems, manufacturing execution systems (MES), cloud computing, and big data analytics to increase operational efficiency and decision-making. These technologies are central to Industry 4.0, which speeds up real-time monitoring, predictive analytics, and the optimisation of processes [37]. Another way in which modern improvement is encouraged by lean management techniques in Industry 4.0 is highlighted in [38]. Lean management is supportive of the major Industry 4.0 aspects, such as continuous improvement, involvement in a supply chain, pull systems, and customer-centric approaches. This paper demonstrates that Industry 4.0 technologies can be used to support lean management. Ref. [39] explained how the digital transformation of SMEs in personalised mass production occurred, with the role of Industry 4.0 supporting the sustainable growth of manufacturing companies. To assist SMEs in achieving mass production tailored to each person, they suggested Lean 4.0. At the same time, [40] also emphasised that the Industry 4.0 readiness of an organisation significantly impacts its ICT infrastructure, especially ERP systems.

Hypothesis 5: *Smart operations significantly impact Industry 4.0 readiness*.

2.6. Relationship Between Smart Operations and Sustainable Manufacturing

Smart operations are essential for sustainable manufacturing, focusing on optimising resource use, minimising waste, and enhancing efficiency [41]. Integrating environmental, social, and governance (ESG) practices into operational processes boosts sustainability by fostering transparency, accountability, and responsible resource use [42]. Successful manufacturing requires embedding sustainability standards to ensure product quality while maximising efficiency and environmental sustainability [43]. Building on the current view of firm capabilities, which emphasises the pivotal role of sustainable resource use and production, this research argues that these elements provide the micro-foundations for capability development and are vital to their ongoing maintenance and growth [44]. Extensive research highlights the importance of firm sustainability capabilities, which include sustainable ESG practices alongside financial assets, as key components for developing SMAR [42].

Hypothesis 6: *Smart operations significantly impact sustainable manufacturing.*

2.7. Relationship Between Smart Products and Industry 4.0 Readiness

Ref. [45] discussed the integration of artificial intelligence (AI) and big data in Industry 4.0, in the context of its contribution to manufacturing, with a specific focus on smart products. As pointed out in [46], the implementation of AI and big data in present-day industries increases the efficiency of production and the quality of the products produced, as well as addressing the security challenges that it presents, such as the privacy and security of the data produced. These products are capable of interacting with their surroundings, gathering information, and helping with independent decision-making. The evolution of intelligent products increases Industry 4.0 readiness because organisations are able to incorporate sophisticated technologies into value chains [23]. The use of technologies, including artificial intelligence, big data analytics, and collaborative robotics, can significantly enhance the efficiency and quality of production, as well as the capabilities of innovation [47,48].

Hypothesis 7: *Smart products significantly impact Industry 4.0 readiness.*

2.8. Relationship Between Smart Products and Sustainable Manufacturing

An important role in the sustainable manufacturing process is performed by smart products, which allow the optimisation of the use of resources, reductions in waste, and improvements in the process of lifecycle management [49]. Predictive maintenance technologies and additive manufacturing help companies to optimise the utilisation of materials, reduce the utilisation of energy, and expand the lifespan of products, thereby improving overall performance in terms of sustainability [50]. In the wider Industry 4.0 concept, artificial intelligence has become a key enabler of intelligent product functionality. It helps to monitor real-time production, optimise processes, and enable adaptive control, contributing to increased operational efficiency and competitiveness [51]. Meanwhile, intelligent systems and, in particular, machine-learning-based systems enable predictive maintenance and condition-based monitoring and can help organisations to detect faults as early as possible and minimise downtime [2].

The growing assimilation of digital technologies has also resulted in the creation of large amounts of operational information produced by connected industrial devices. When used appropriately, these data can enhance the accuracy of diagnosis, optimise the use of equipment, and enable informed decisions throughout the product lifecycle. Moreover, additive manufacturing technologies can be associated with unique benefits to sustainability, as they allow for reducing the amount of material waste, decreasing the energy demand, and creating lightweight products [50]. These functions combined make smart products one of the key tools in the digital transformation regarding the creation of sustainable products.

Furthermore, smart product development is closely connected with additive manufacturing and wider Industry 4.0 integration, particularly where product data, digital design, simulation, and manufacturing systems are linked through a digital thread. Ref. [8] argues that the interrelationship between additive manufacturing and Industry 4.0 technologies can strengthen smart manufacturing by improving responsiveness to customer requirements, enabling more complex product configurations, and supporting digitally integrated production systems. This reinforces the view that smart products contribute to sustainable manufacturing most effectively when product intelligence, lifecycle data, and manufacturing technologies are integrated rather than treated as separate digital initiatives.

Hypothesis 8: *Smart products and sustainable manufacturing are significantly associated.*

2.9. Relationship Between Data-Driven Services and Industry 4.0 Readiness

Data-driven services have become a vital element of the digital transformation, with a focus on the application of data analytics in decision-making and value creation. Readiness is the necessary condition to embrace a certain innovation or participate in a certain activity [52]. Companies that have greater readiness rates are better positioned to implement data analytics projects successfully and gain competitive advantages [53]. A culture that is willing and ready to use data to make informed decisions is needed to be successful in a data-driven organisation—including not only the correct technology and data infrastructure but also the culture. Moreover, a culture of continuous learning and development is necessary to leverage big data [54]. Ref. [55] suggests that organisations should have certain readiness factors, such as leadership and top management support, an organisational culture that embraces change, employee buy-in, awareness of the change initiative, and customer and supplier buy-in.

Hypothesis 9: *Data-driven services and Industry 4.0 readiness are significantly associated.*

2.10. Relationship Between Data-Driven Services and Sustainable Manufacturing

Furthermore, data-driven services contribute to sustainable manufacturing by enhancing decision-making, improving process efficiency, and enabling continuous improvement [56]. Businesses need an appropriate culture to derive value from their work and benefit from business analytics solutions at a high level [57]. A strong data-driven culture fosters innovation, knowledge sharing, and organisational learning, which are essential for achieving sustainability goals. A data-driven organisational culture, on the other hand, focuses on the functions of the organisation and management-level findings, as well as transforming data into decisions [58]. An appropriate culture in the digital age is data-driven. This is because a data-driven culture enhances learning, communication, and knowledge sharing and successfully transforms and implements new ideas and processes [59]. While numerous factors influence big data analytics readiness, it is widely acknowledged that there are a few common themes regardless of industry; these are the organisational structure, IT infrastructure, open communication, optimised business processes, the measurement of key performance indicators, and a culture of trust [4,55].

Hypothesis 10: *Data-driven services and sustainable manufacturing are significantly associated.*

2.11. Relationship Between Employees and Industry 4.0 Readiness

Employees represent a fundamental organisational condition for Industry 4.0 readiness, as digital transformation depends not only on technological availability but also on the capabilities of the workforce to interpret, adopt, and use advanced systems effectively [60]. The implementation of Industry 4.0 technologies, therefore, requires employees with relevant technical skills, adaptability, and a willingness to engage with new forms of digital work [61]. Capacity building among employees, especially through training, reskilling, and constant professional development, enhances organisational readiness by making the workforce competent and responsive to the change in technology. Companies that strategically invest in human capital have higher chances of creating the internal capacity needed to undertake digital transformation initiatives successfully [62]. In this respect, employee readiness goes beyond technical competence; it encompasses behavioural readiness, learning orientation, and openness to organisational change.

Previous studies also suggest that employee-related readiness may be more decisive than mere structural or technological factors regarding the success of change programmes. As a result, change agents, practitioners, and researchers continue to discuss how various combinations of positive employee readiness factors can facilitate the successful implementation of organisational change [63].

Hypothesis 11: *Employees and Industry 4.0 readiness are significantly associated.*

2.12. Relationship Between Employees and Sustainable Manufacturing

The capabilities of the employees occupy centre stage in the realisation of sustainable manufacturing because sustainability-oriented production must not only be technologically advanced but also requires a workforce that is capable of applying the knowledge, improving the processes, and supporting the responsible practices of operations. When employees are empowered through constant learning and development, they contribute to increased operational efficiency, greater innovation, and better performance of the organisation [64]. This aspect promotes adaptability, which is crucial to sustainability performance in the face of evolving technological and market conditions [65]. The capacity building of employees, such as the development of knowledge, skills, and practical experience, has been widely recognised as being an important determinant of the quality of organisational performance [66]. Within manufacturing companies, particularly SMEs, organised capability development programmes can enhance resilience in the event of technological changes, as well as promoting more sustainable patterns of growth. These initiatives can increase organisational capabilities by enhancing operational performance, innovation, and competitiveness but also contribute to more responsible resource use.

In the same vein, organisational capacity-building practices based on continuous knowledge acquisition and skill development offer a platform for enhanced organisational performance. These investments can serve as catalysts for innovation, flexibility, and long-term competitive advantage, thereby solidifying the human capability foundation of sustainable manufacturing [67]. Thus, it is possible to consider employees as a critical enabling resource through which firms can translate learning, skills, and adaptive capacity into sustainable manufacturing results.

Hypothesis 12: *Employees and sustainable manufacturing are significantly associated.*

2.13. Relationship Between Industry 4.0 and Sustainable Manufacturing

Digital technologies are considered a constituent element of environmentally friendly decisions in manufacturing because they assist in the optimisation of resource use and, in turn, in reducing harmful effects on the environment [19]. Overall, the benefits of Industry 4.0 for sustainability are likely to be experienced in the following: improving productivity, flexibility, resource efficiency, the reduction of waste, energy consumption, reduced overproduction, and the creation of employment opportunities for disabled and elderly workers. Ref. [68] places an emphasis on the application of Industry 4.0 technologies that result in sustainable and transparent production strategies. As an example, predictive maintenance and real-time analytics can help to decrease energy consumption and enhance the efficiency of equipment, which contributes to environmental sustainability [18]. Although there are differences, the current body of literature tends to endorse a positive relationship between the implementation of Industry 4.0 and its sustainability performance.

Hypothesis 13: *Industry 4.0 and sustainable manufacturing are significantly associated with each other*.

2.14. Mediating Relationship of Industry 4.0 Readiness Between Strategy and Organisation and Sustainable Manufacturing

The ability of a firm to embrace and institutionalise sustainable manufacturing practices is centred on strategic orientation and the organisational structure [15]. However, strategic intent in isolation will not yield sustainability results unless it is enabled by a sufficient level of Industry 4.0 readiness. Industry 4.0 readiness in this relationship acts as an enabling mechanism where strategic priorities and organisational arrangements are transformed into operational sustainability [69]. Companies that have well-defined digital strategies, dedicated leaders, and flexible organisational structures are more likely to establish the readiness needed to implement Industry 4.0. This readiness is the integration of technological infrastructure, governance, cross-functional coordination, and an innovation-oriented culture. Together, these factors contribute to the successful implementation of Industry 4.0 technologies and help companies to optimise resource use, enhance process efficiency, and minimise environmental impacts [27].

Moreover, the availability of real-time data and the integration of cyber-physical systems enable organisations to make more informed operational decisions, minimise process inefficiencies, and reduce waste [70]. In this respect, the organisational route through which strategy and structure can impact sustainable manufacturing is Industry 4.0 readiness. Without such readiness, even carefully designed strategies can be aspirational and unable to deliver measurable sustainability benefits.

Hypothesis 14: *Industry 4.0 readiness mediates the relationship between strategy and organisation and sustainable manufacturing*.

2.15. Mediating Relationship of Industry 4.0 Readiness Between Smart Factory and Sustainable Manufacturing

Smart factories, which are characterised by interconnected systems, the integration of cyber and physical components, and the real-time exchange of data are one of the core pillars of Industry 4.0 implementation [71]. The effectiveness of smart factory technologies will lie in how much organisations are prepared to implement, integrate, and utilise these technologies. Readiness is thus an important organisational context in which intelligent factory adaptability can be translated into sustainable production outcomes. When it comes to digital and analytics-driven change, organisational readiness is often linked to the presence of financial resources, information technology infrastructure, and a workforce that is able to implement and utilise advanced technologies efficiently [55]. However, readiness goes beyond the availability of resources. It also encompasses organisational processes, managerial commitment, technical competence, and the cultural conditions necessary to facilitate change using technology. Previous studies in the field of big data and business analytics also recognise organisational readiness as a precondition to achieve successful implementation and value creation [54].

To this end, Industry 4.0 readiness enables firms to translate smart factory investments into sustainability gains by ensuring that the requisite skills, infrastructure, governance systems, and improvement processes are in place [72]. In the absence of such readiness, any investment in automation, connectivity, or real-time monitoring can be left fragmented and failing to produce any meaningful sustainability gains.

Hypothesis 15: *Industry 4.0 readiness mediates the relationship between smart factories and sustainable manufacturing*.

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2.16. Mediating Relationship of Industry 4.0 Readiness Between Smart Operations and Sustainable Manufacturing

Smart operations refer to the incorporation of advanced digital systems, such as enterprise resource planning, manufacturing execution systems, cloud technologies, and data analytics, to enhance operational efficiency and decision-making [73]. These technologies have significant sustainability potential through the support of process optimisation, waste reduction, and resource efficiency and the real-time control of operations. Nevertheless, their role in sustainable manufacturing will likely depend on the extent to which the organisation is Industry 4.0-ready. Industry 4.0 readiness offers both an organisational and technical basis on which to effectively integrate operational technologies [74]. It also supports the interoperability of systems, accuracy of data, coordination of processes, and real-time decision-making, which are all required when converting smart operational capabilities into sustainability [75]. Readiness also helps to adopt digitally enabled quality management practices, such as Quality 4.0, where digital tools are utilised to enhance the performance of processes, product quality, and continuous improvement practices [4].

With such mechanisms, digitally prepared organisations are more able to mitigate inefficiencies, streamline resource utilisation, and introduce sustainable measures across the production and operational system [14]. In this way, the correlation between smart operations and sustainable manufacturing is not purely direct but is reinforced by the fact that the organisation is able to absorb, coordinate, and operationalise Industry 4.0 technologies [55].

Hypothesis 16: *Industry 4.0 readiness mediates the relationship between smart operations and sustainable manufacturing.*

2.17. Mediating Relationship of Industry 4.0 Readiness Between Smart Products and Sustainable Manufacturing

Smart products, which are sensor-equipped, connected, and communicative products, make real-time interaction between products, users, and production systems possible [76]. These capabilities have the potential to facilitate sustainable manufacturing by improving the management of the lifecycles of products, enabling predictive maintenance, reducing waste, and increasing resource efficiency. However, the sustainability contribution of smart products is determined by whether firms have the readiness to capture, interpret, and apply product-related data effectively. Industry 4.0 readiness provides the technological basis, analytical potential, and human resource competency to transform smart product data into operational and sustainability enhancement [77]. Studies conducted in the past have used readiness assessment to rank key criteria, drivers, and technologies to adopt Industry 4.0 among SMEs, illustrating its relevance in informing the decision to be digital [31]. On the same note, readiness-based models have been established to measure transition readiness and assist practitioners in assessing maturity in key areas of smart product design and development [78].

In line with this, Industry 4.0 readiness can be perceived as the process by which smart product functionalities can impact sustainable manufacturing [79]. With readiness, organisations can be more efficient in their application of predictive maintenance, data-refined design, and the optimisation of their lifecycles in a way that minimises material waste, enhances energy efficiency, and strengthens product sustainability.

Hypothesis 17: *Industry 4.0 readiness mediates the relationship between smart products and sustainable manufacturing.*

2.18. Mediating Relationship of Industry 4.0 Readiness Between Data-Driven Services and Sustainable Manufacturing

Data-driven services are defined as the application of big data, analytics, and digital intelligence to facilitate decision-making, service innovation, and value creation [80]. Such services have the potential to accelerate sustainable manufacturing through process visibility and evidence-based decision-making, the reduction of inefficiencies, and continuous improvement. Nevertheless, they can be effective only when the organisation is ready to develop and maintain a data-driven culture [57]. Readiness for Industry 4.0 allows organisations to develop the infrastructure, skills, governance mechanisms, and cultural orientation that they will need to transform their data into action [81]. It encourages the incorporation of analytics in managerial and operational decision-making, enabling firms to recognise inefficiencies, minimise waste, and enhance sustainability performance. Organisational readiness also promotes organisational learning and sustained improvement, which are critical in transforming data-driven insights into pragmatic sustainability outcomes [55].

In the absence of adequate readiness, companies might generate vast amounts of information without the ability to interpret, share, or put it to meaningful use. In this situation, the potential of data-driven services to be sustainable can be left unrealised. Industry 4.0 readiness thus offers a mediating channel in which data-driven services can be applied in achieving sustainable manufacturing performance [82].

Hypothesis 18: *Industry 4.0 readiness mediates the relationship between data-driven services and sustainable manufacturing*.

2.19. Mediating Relationship of Industry 4.0 Readiness Between Employees and Sustainable Manufacturing

The ability of the employees is a major requirement for organisational change and manufacturing that is geared towards sustainability. A well-trained workforce is more likely to adopt new technologies, participate in process innovation, and contribute to practices that enhance operational efficiency and environmental performance [83]. Nevertheless, the role of the organisation is in providing the digital infrastructure, training systems, and managerial support needed to ensure that individual capabilities are translated into shared performance. Industry 4.0 readiness will increase the effectiveness of employees as workers are provided with access to advanced tools, structured training, digital systems, and supportive change processes [84]. Once employees feel that their development is supported, they are more likely to exhibit engagement, commitment, and motivation, and organisations may experience reduced turnover and stronger performance aligned with a sustainability orientation. Readiness also contributes to ongoing learning and flexibility, both of which are important in maintaining performance in manufacturing industries that are technology intensive [85].

Those employees who work in an organisation that is digitally prepared are thus better placed to adopt sustainable practices, respond to environmental pressures, and support innovation-led improvement [86]. Industry 4.0 readiness is a mediating factor that transforms employees' potential into sustainable production outcomes [87]. In the absence of this organisational readiness, the skills of employees might be underutilised, and the contribution of employees to sustainability might be limited.

Hypothesis 19: *Industry 4.0 readiness mediates the relationship between employees and sustainable manufacturing*.

2.20. Underpinning Theories

This study is grounded in the technology–organisation–environment (TOE) framework, the resource-based view, and dynamic capabilities theory. Together, these perspectives explain how technological conditions, organisational resources, external pressures, and adaptive capabilities shape Industry 4.0 readiness and, subsequently, sustainable manufacturing outcomes.

2.20.1. Technology–Organisation–Environment (TOE) Framework

The technology–organisation–environment model is used to explain the adoption of technological innovation in three inter-related contexts: technological, organisational, and environmental conditions [88,89]. The technological context used in this study encompasses Industry 4.0 tools and infrastructures, such as artificial intelligence, IoT, cyber-physical systems, smart factory technologies, analytics platforms, and data-driven services [45]. They are adopted according to their perceived compatibility, complexity, functionality, and relative advantage.

The organisational environment deals with internal readiness requirements, such as leadership dedication, assets, governance, culture, staff competence, and operational practices. These aspects are essential since digital transformation involves not only purchasing technology but also organising people, processes, and structures. The environmental context represents external forces, including regulatory expectations, competitive pressure, customer requirements, supply-chain demands, sustainability policies, and national agendas of digitalisation [90]. The TOE framework thus aids the view of the study that Industry 4.0 readiness comes about through the interplay of technological potential, organisational capacity, and external pressure.

2.20.2. Resource-Based View

The resource-based view interprets firm performance in terms of internal resources and capabilities that are valuable, rare, inimitable, and non-substitutable [91–93]. This paper considers smart factory systems, smart operations, smart products, data-driven services, and skilled employees as strategic resources that can be used to drive efficiency, innovation, responsiveness, and sustainability performance. Nevertheless, the RBV also warns that the possession of resources does not guarantee better results. Digital technologies can be underused when firms do not have the organisational capacity to integrate and make good use of them. The state of being Industry 4.0-ready is therefore positioned as the facilitating condition whereby technological and human resources are translated into sustainable manufacturing products.

2.20.3. Dynamic Capabilities Theory

Dynamic capabilities theory is an extension of the RBV that explains how firms adapt, integrate, and reconfigure resources in changing environments. According to [94], dynamic capabilities facilitate firms in sensing, seizing, and transforming operations. This concept especially applies to Industry 4.0, where technological change is swift, intricate, and disruptive. Readiness for Industry 4.0 can thus be perceived as a reflection of dynamic capabilities. It embodies a firm's ability to internalise digital technologies, foster organisational learning, enhance innovation competence, and promote workforce flexibility [95]. By doing so, companies can align smart factory systems, smart operations, smart products, data-driven services, and employee competencies with sustainability goals. In this connection, dynamic capabilities theory offers the key logic for explaining readiness as the mediating variable between IMPULS dimensions and sustainable manufacturing performance.

Building on this theoretical foundation, the study advances 19 hypotheses that specify the direct relationships among the six IMPULS dimensions, Industry 4.0 readiness, and sustainable manufacturing, as well as the indirect relationships transmitted through I4.0 readiness. These hypotheses were tested using partial least squares structural equation modelling to validate the proposed IMPULS-informed framework and to examine how organisational and technological capabilities are transformed into sustainable manufacturing outcomes.

3. Methods

3.1. Research Design

This study adopted a quantitative, cross-sectional research design to examine how the six IMPULS dimensions influence Industry 4.0 readiness and sustainable manufacturing in the Pakistani manufacturing sector. This study is grounded in the positivist research philosophy, which emphasises objectivity, quantifiable observations, and generalisable findings [96]. A survey design was considered appropriate because the study required standardised, comparable responses across firms operating in different manufacturing segments. Consistent with prior Industry 4.0 readiness research, the design enabled the empirical assessment of multiple direct and mediating relationships within a single structural model [27,97]. To strengthen construct alignment, the research design was also guided by an operational measurement framework that linked the IMPULS dimensions with Industry 4.0 enablers, key readiness factors, and item-level indicators. This framework ensured that the survey instrument reflected both the conceptual logic of Industry 4.0 readiness and the contextual realities of Pakistani manufacturing firms. The cross-sectional approach was suitable for capturing firms' current readiness and sustainability-related practices, although it does not permit claims about changes over time.

3.2. Population and Source of Data

The target population comprised manufacturing organisations operating in Pakistan. The sample covered several key sectors represented in the dataset, including food and beverages; agro-processing; electronics and electrical manufacturing; textiles and garments; automotives and engineering; pharmaceuticals and medical equipment; iron, steel, and metal; and chemicals and plastics. This sectoral spread was important because Industry 4.0 readiness is not uniform across manufacturing contexts; digital infrastructure, automation exposure, workforce capabilities, and sustainability pressures differ materially across industries.

The unit of analysis was the organisation, while the respondents were individuals with sufficient knowledge of manufacturing operations, digitalisation, sustainability practices, or strategic decision-making. This included directors, CEOs, managers, engineers, technical staff, operations personnel, IT and production managers, and supply-chain professionals. Such respondents were considered appropriate because Industry 4.0 readiness involves strategic, operational, technological, and human resource dimensions rather than a single functional domain.

3.3. Sampling Technique

The sampling was performed via two-stage non-probability sampling, which consisted of a combination of purposive and snowball sampling. Purposive sampling was used to ensure that the sample had appropriate professional exposure to manufacturing processes, the adoption of technology, or organisational change. Snowball sampling was then employed to contact other eligible respondents using professional referrals. Such a hybrid strategy was suitable due to the practical challenges involved in reaching manufac-

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turing professionals working in geographically dispersed companies, as well as the need to obtain responses from individuals who were knowledgeable regarding issues related to Industry 4.0.

This methodology was informed by similar Industry 4.0 readiness studies, where the respondents were asked to take part due to their positions in the office; this is capable of providing informed organisational-level judgments rather than general opinions. The final sample of 470 usable responses substantially exceeded the minimum threshold. This strengthened the statistical adequacy of the model, particularly because the study tested multiple latent constructs, mediation paths, and measurement model properties.

3.4. Data Collection Procedures

The data were gathered using a structured questionnaire given to respondents working in the manufacturing sector in Pakistan. The total number of questionnaires distributed was more than 1100, with 470 usable responses being obtained, which equates to an approximately 42.7 percent response rate. The partner institutions, such as the University of the Punjab, Lahore and Thal University, Bhakkar, provided support in data collection through webinars and professional engagement activities. Additional responses were received via LinkedIn, networks in the manufacturing sector, and referrals from participants who had worked in a relevant job in an industrial setting.

The mixed recruitment strategy was adopted due to access limitations in the manufacturing industry. An estimated 67% of the responses were gathered via direct interaction, such as webinars and professional interactions, and approximately 33% of the responses were collected through professional referrals. This method enhanced the coverage of respondents across various organisational functions, manufacturing divisions, and sustainability processes.

3.5. Research Instrument

This study employed a quantitative approach, combining a survey and a questionnaire [96]. The questionnaire was constructed based on existing and validated measurement scales. It included eight constructs: strategy and organisation, smart factories, smart operations, smart products, data-driven services, employees, Industry 4.0 readiness, and sustainable manufacturing. These constructs were congruent to the IMPULS framework and the theoretical positioning of this study.

All items were measured as part of a five-point Likert scale, allowing the respondents to respond to the statements in question and express their levels of agreement with them. The Likert format was suitable since the constructs of interest were perceptual measures of organisational capabilities, readiness, and the implementation of sustainability. Content validity was enhanced by the use of previously validated scales, which also helped to compare the results with prior Industry 4.0 readiness research. Table 1 below shows the number of items that was adopted for each construct.

As depicted in Tables 1–3, the questionnaire was operationalised through a structured framework that linked the six IMPULS dimensions with relevant Industry 4.0 enablers, key readiness factors, and item-level measures. This framework provided a transparent connection between the conceptual model and the empirical instrument by showing how each construct was translated into measurable survey indicators.

Table 1. IMPULS-informed dimensions, Industry 4.0 enablers, and key readiness factors.

Sr. #	IMPULS Dimension	Industry 4.0 Enablers	Key Readiness Factors	Items	References
1	Strategy and Organisation	New business models, horizontal/vertical integration	Management support and leadership (top management commitment, strategy alignment)	Our organisation has the necessary support from top management to work on Industry 4.0.	[98,99]
			Government supportive policies	Government incentives and policies support our digital transformation.	
			Financial support	The government provides financial support for the adoption of new industrial technologies.	
			Cross-functional collaboration and transparency	There is strong collaboration between different departments to support digital transformation and Industry 4.0.	
			Sustainability integration	The organisation is sustainable with its existing operations.	
			Competitiveness	Our employees have the right competencies to cope with Industry 4.0 competitiveness.	
			Continuous improvement culture	Our organisation is creating an open culture for innovation and creativity to support digital transformation.	
			Risk and benefit management	Our organisation is willing to take risks and experiment with Industry 4.0.	
			Innovation management	Managers are well-equipped to make decisions about adapting to new technology.	
2	Smart Factory	IoT, cyber-physical systems, digital twins	Automation level (IoT-enabled machinery, M2M communication, IT-controlled systems)	Our machinery is capable with IoT sensors, enabling real-time data collection, and machine-to-machine (M2M) communication is actively used to automate workflows.	[2,100,101]
			Compatibility with existing technology	Our machines and infrastructure have been connected through IT systems for machine-to-machine [M2M] communications.	
			Cyber-physical systems	Our cyber-physical systems (CPS) are integrated with real-time monitoring and control.	
			Digital twins	We use digital twins to simulate and mirror our physical processes.	
3	Smart Operations	Big data analytics, AI, cybersecurity	End-to-end digital process integration	Processes across our digital value chain are integrated from start to finish.	[8,102]
			Mobile and remote access	Maintenance staff regularly use mobile devices for real-time diagnostics.	
			IT security and data privacy	For all pertinent sectors, IT security solutions have been put in place.	
			Process transparency	Key performance indicators are automatically tracked and visible to all users.	
			Digital workflow management	Stakeholders have real-time visibility into digital process workflows.	
			Supply chain management and collaboration	Senior management uses I4.0 to engage in decision-making processes for sustainable SC management strategies.	

Table 1. *Cont.*

Sr. #	IMPULS Dimension	Industry 4.0 Enablers	Key Readiness Factors	Items	References
4	Smart Products	IoT, augmented reality, AI	Product connectivity (IoT-enabled)	Our company's products are equipped with ICT components.	[6,103]
			Lifecycle data management	Our products have been built with ICT add-on functionalities that allow information to be sent back to the manufacturer throughout the product's lifecycle.	
			Integration with digital services	Digital IT systems are integrated and assist all business processes.	
			Remote monitoring and diagnostics	Systems and machines can be remotely monitored entirely by IT and are well-integrated.	
			Product customisation/configurability	Our company uses data to develop new products, customisation support, sales, and after-sales services (e.g., tele-maintenance).	
5	Data-Driven Services	Big data analytics, cloud computing, digital platforms	Development of new digital services	The product offers data-driven services, which the company plans to integrate with its services for its customers.	[103–105]
			Autonomous process	Autonomous process is used in selected areas or even across enterprises.	
			Data analytics for service optimisation	The data-driven services have played an important role in our optimisation.	
			Platform/improve service model	The information collected is used to develop and improve service models for our company.	
			Data privacy	Our company has a culture that prioritises externalising data privacy.	
6	Employees	Human–machine collaboration, digital literacy	Digital skills and competencies	The organisation needs employees to have knowledge and understanding and basic skills for working towards Industry 4.0 in all departments.	[6,104,106]
			Training and development programmes	The training is provided to our existing employees to adapt to the IT-embedded manufacturing system.	
			Employees involvement in digital projects	Employees have the required expertise to operate the digitised equipment and machinery.	
			Collaboration and knowledge sharing	Our teams have strong coordination and collaboration among members for digital transformation.	

The six IMPULS dimensions were mapped as follows: strategy and organisation addressed leadership, policy support, financial support, collaboration, innovation culture, sustainability integration, and risk management; smart factory captured IoT-enabled machinery, machine-to-machine communication, cyber-physical systems, and digital twins; smart operations reflected process integration, remote access, IT security, workflow visibility, and supply-chain collaboration; smart products focused on product connectivity, lifecycle data, digital service integration, remote monitoring, and customisation; data-driven services captured digital service development, autonomous processes, analytics, service model improvement, and data privacy; and employees reflected digital skills, training, employee involvement, and knowledge sharing.

Table 2. Industry 4.0 readiness and its subconstructs.

Sr. #	Dependent Construct	I4.0 Readiness Subconstruct	Items	References
1	Industry 4.0 Readiness	Managerial Readiness	Our management is convinced that we must implement the digital transformation process.	[27]
			Our company has the right leadership in place to implement digitalised production.	
			Our management has approved a budget for upgrading production processes.	
			Our management is recruiting new staff necessary for upgrading the production process.	
		Operational Readiness	Our company is financially prepared to digitalise operations to Industry 4.0 standards.	
			Our company has staff to manage the digital transformation/Industry 4.0 standards.	
			Our company has the infrastructure to support the digital transformation and Industry 4.0 production process.	
			Our company has the resources to start digital transformation.	
		Technological Readiness	Our company has an IT system that can be upgraded for the Industry 4.0 production process.	
			Our key machines and equipment can be networked for the Industry 4.0 process.	
			Technical training has been provided for our staff to understand the digital transformation process.	
			Our company has vendors who can provide good services for the technical aspect of digital transformation.	

Table 3. Operationalisation of sustainable manufacturing.

Sr. #	Moderating Construct	Items	References
1	Sustainable Manufacturing	Our company actively reduces material waste during production processes.	[107,108]
		Our company's sustainability practices improve cost efficiency.	
		Our company invests in modern technologies to improve industrial productivity.	
		Our company's infrastructure is resilient and adaptable to digital transformation.	
		Our company's products are designed for reuse, recycling, or remanufacturing.	
		Our company complies with national and international sustainability standards and certifications and regulations (e.g., ISO 14001).	
		Our company uses eco-friendly materials and processes wherever possible for setting sustainable targets and objectives.	
		Our sustainability practices improve manufacturing and machine efficiency.	

Industry 4.0 readiness was measured through managerial, operational, and technological readiness, allowing readiness to be assessed as a multidimensional organisational condition.

Sustainable manufacturing was operationalised through indicators covering waste reduction, cost efficiency, modern technology use, infrastructure resilience, circular product design, regulatory compliance, eco-friendly processes, and manufacturing efficiency.

This framework strengthened the methodological transparency by clarifying how the IMPULS-informed framework was adapted to the Pakistani manufacturing context and how each construct was empirically measured. This is conceptually reflected in the research model shown in Figure 1.

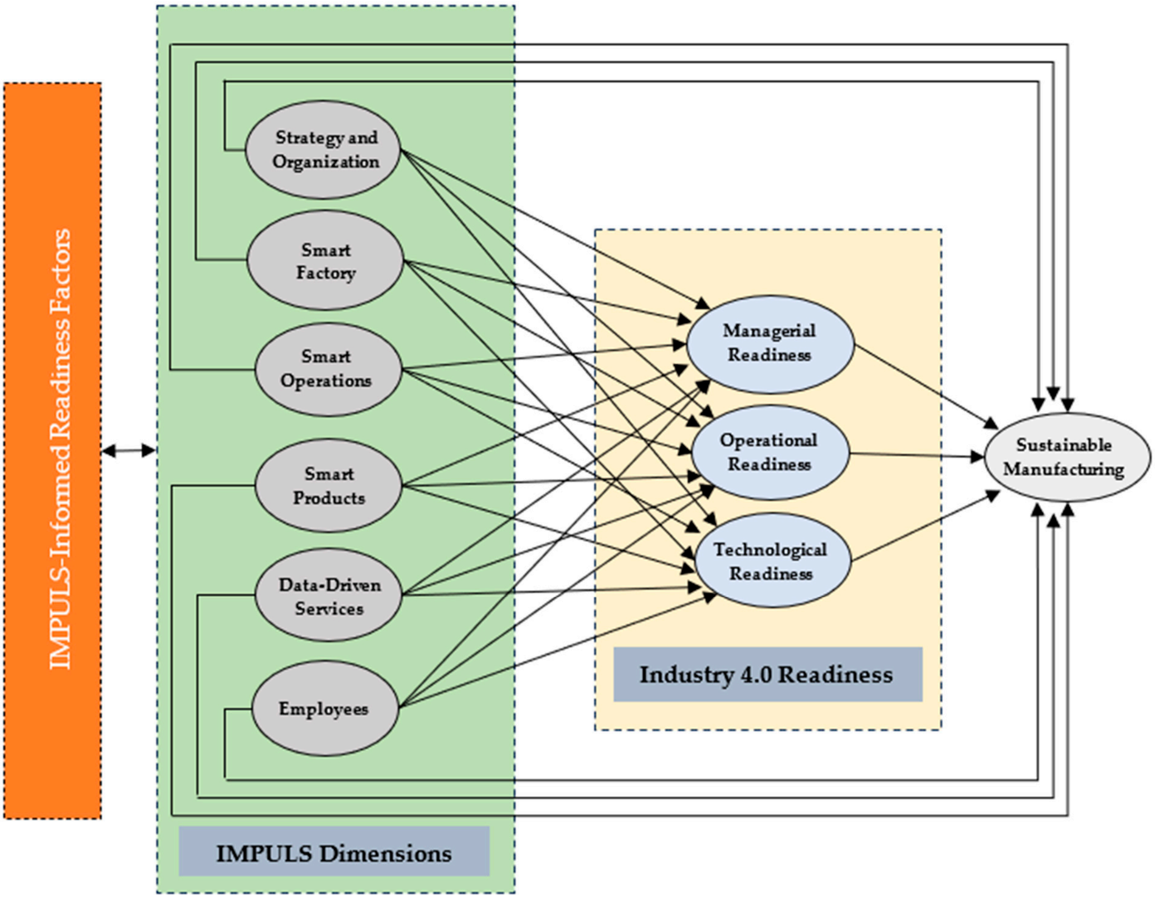

Figure 1. IMPULS-informed framework for evaluating organisational readiness for Industry 4.0 transformation.

3.6. Common Method Bias

Since the data were gathered using a single survey instrument, common method bias was addressed through both procedural and statistical measures. The procedures included informing the respondents that there were no correct or incorrect answers and that their responses were anonymous to reduce evaluation apprehension and social desirability bias. These are common solutions prescribed in organisational research that is based on surveys [109]. The single-factor test and full collinearity diagnostics of the test were statistically used to determine whether a single factor in the covariance structure dominated. Moreover, the variance inflation factor values were analysed as part of the structural model evaluation.

3.7. Statistical Techniques and Data Analysis

The data were analysed using SPSS ver. 31.0.2.0 and SmartPLS ver. 4.1.1.7. Data screening, descriptive statistics, missing value checks, and pre-diagnostic analyses were performed in SPSS. The measurement and structural models were estimated using Smart-

PLS with partial least squares structural equation modelling. PLS-SEM was suitable because the research involved several latent constructs, a fairly complex model structure, mediation analysis, and prediction-oriented theoretical objectives [97,110].

The analysis was performed in a staged manner. To begin with, the data were investigated for completeness, outliers, and distributional characteristics. Second, the respondent and firm profiles were summarised using descriptive statistics. Third, indicator loadings, Cronbach's alpha, composite reliability, rho A, average variance extracted, and discriminant validity were used to evaluate the reflective measurement model. Fourth, the structural model was assessed in terms of collinearity diagnostics, standardised path coefficients, bootstrapped significance values, $R^{2,}$ adjusted $R^{2,}$ f^2 effect sizes, and mediation effects. This sequence is consistent with the current PLS-SEM reporting requirements, where the quality of measurement has to be established first, and only substantive structural claims can be interpreted [97,111].

3.8. Measurement Model Evaluation

The measurement model was tested to determine its reliability and validity. The reliability of the indicators was measured using the outer loadings, whereby the greater the loadings, the greater the association between the indicators and their intended constructs. Cronbach's alpha, rho A, and composite reliability were used to test internal consistency reliability. The average variance extracted was used to measure convergent validity, with a value greater than 0.50 indicating that the construct explained more than half of the variance in its indicators [97].

The heterotrait–monotrait ratio of correlations was used to determine the discriminant validity. The reason that HTMT has become more popular than the traditional Fornell–Larcker criterion is that it is a more sensitive test of whether constructs are empirically distinct or not [111]. This was particularly crucial in the present study due to the conceptual relations among several IMPULS dimensions, including smart operations, smart products, smart factories, and employees.

3.9. Structural Model Evaluation

After establishing the adequacy of the measurement model, the structural model was assessed. Inner VIF values were used to assess collinearity among predictor constructs. Path coefficients were then estimated to ascertain the strength and direction of the hypothesised relationships. The statistical significance, confidence intervals, and strength of direct and indirect effects were assessed using bootstrapping with 5000 subsamples.

The explanatory power of the model was evaluated based on the values of R^2 and adjusted R^2 for Industry 4.0 readiness and sustainable manufacturing. To test effect sizes, the f^2 was used to test the real contribution of each exogenous construct. A mediation analysis was conducted to assess the mediating role of Industry 4.0 readiness in transmitting the effects of the IMPULS dimensions on sustainable manufacturing. When predictive statistics are known, Q^2 or PLS prediction ought to be reported to enhance the model's predictive evaluation, as recommended in the recent PLS-SEM literature [110].

4. Data Analysis and Results

4.1. Respondents' Demographic Profile

This study analysed 470 usable responses from firms across a diverse range of manufacturing sectors. Table 4 shows that the largest sectoral shares came from food and beverages (17.0%), agro-processing (15.5%), and electronics and electrical (13.0%), indicating broad industrial representation. Large firms (30.6%) and small firms (29.8%) dominated the sample, while 48.7% of firms had been operating for 11 to 20 years. Joint ventures constituted the majority ownership form (71.5%), and limited companies represented the largest legal status category (37.7%). Most respondents were engineers/technical staff (24.9%), followed by directors/CEOs (18.1%) and management/leadership (17.0%). In terms of digital maturity, 39.8% reported being somewhat aware of Industry 4.0, while 65.3% indicated moderate prior adoption of digital or automation technologies. Overall, the sample reflects substantial diversity across sectors nationwide in terms of organisational size, ownership, and respondent roles, supporting the dataset's adequacy for examining Industry 4.0 readiness and sustainable manufacturing.

Table 4. Demographic profile of respondents and firms.

Variable	Category	Frequency	Percentage
Industry Type	Food and beverages	80	17.0
	Agro-processing	73	15.5
	Electronics and electrical	61	13.0
	Textiles/garments	57	12.1
	Automotives/engineering	48	10.2
	Pharmaceuticals/medical equipment	47	10.0
	Iron, steel, and metal	44	9.4
	Chemicals and plastics	32	6.8
	Other	28	6.0
Firm Size	Large (>500)	144	30.6
	Small (50–200)	140	29.8
	Medium (201–500)	96	20.4
	Micro (<50)	90	19.1
Firm Age	1–10 years	144	30.6
	11–20 years	229	48.7
	21–30 years	97	20.6
Ownership Type	Joint venture	336	71.5
	Foreign-owned	99	21.1
	Local	35	7.4
Legal Status	Limited	177	37.7
	Partnership	124	26.4
	Sole proprietorship	93	19.8
	Public listed	76	16.2
Industry 4.0 Awareness	Somewhat aware	187	39.8
	Not aware	163	34.7
	Fully aware	120	25.5
Geographical Location	Islamabad Capital Territory	108	23.0
	Punjab	107	22.8
	KPK	74	15.7
	Sindh	73	15.5
	Other	55	11.7
	Balochistan	53	11.3
Respondent Position	Engineer/technical staff	117	24.9
	Director/CEO	85	18.1
	Management/leadership	80	17.0
	Executive/manager (operations/IT/production)	79	16.8
	Supply chain/logistics officer	61	13.0
	Other	48	10.2
Previous Adoption of Digital/Automation Technologies	Moderate (ERP, basic automation)	307	65.3
	Minimal/none	96	20.4
	Advanced (IoT, AI, robotics)	67	14.3

4.2. Measurement Model Assessment

The reflective measurement model was evaluated in terms of indicator reliability, internal consistency reliability, convergent validity, and discriminant validity. The corrected PLS solution had strong outer loadings in general. Strategy and organisation ranged from 0.718 to 0.795, smart factory from 0.811 to 0.846, smart operations from 0.748 to 0.831, smart products from 0.708 to 0.869, employees from 0.832 to 0.920, Industry 4.0 readiness from 0.700 to 0.850, and sustainable manufacturing from 0.791 to 0.857. The weakest block was data-driven services, which had retained loadings of 0.735, 0.849, and 0.607. Bootstrapping revealed that all indicators retained were significant at $p < 0.057$, although only DDS4 was significant (t = 1.905, $p = 0.057$). This implies that the underlying empirically less stabilised and empirically thinner data-driven service capability is a more mature strategic, operational, and workforce dimension.

The results regarding internal consistency and convergent validity were satisfactory. The composite reliability, according to Table 5, ranged between 0.778 and 0.947, and the AVE was between 0.543 and 0.777, which are higher than the recommended values of 0.70 and 0.50, respectively [97,112]. Cronbach's alpha was also acceptable in all constructs, with the exception of data-driven services (0.607).

Table 5. Reliability and convergent validity statistics.

Construct	Alpha	rho_A	CR	AVE
Data-Driven Services	0.607	0.652	0.778	0.543
Employees	0.904	0.904	0.933	0.777
Industry 4.0 Readiness	0.889	0.894	0.914	0.604
Smart Factory	0.846	0.847	0.896	0.684
Smart Operations	0.900	0.901	0.921	0.625
Smart Products	0.830	0.839	0.888	0.665
Strategy and Organisation	0.900	0.903	0.920	0.589
Sustainable Manufacturing	0.937	0.937	0.947	0.693

Some pairs of constructs were well below the conservative 0.85 level, especially those that involved data-driven services. Nonetheless, higher HTMT values, as shown in Table 6, were observed between constructs that were conceptually proximate, such as smart products–employees (0.956), smart products–smart operations (0.949), smart operations–smart factory (0.910), and sustainable manufacturing–Industry 4.0 readiness (0.966). The bootstrapped HTMT confidence intervals of these pairs were less than 1.0, providing minimal statistical support for discriminant validity, but the magnitude of the ratios indicates that some dimensions are empirically close and should be interpreted as tightly interconnected rather than sharply isolated organisational capabilities.

Table 6. Selected HTMT ratios and bootstrapped confidence intervals.

Construct Pair	HTMT	Lower CI	Upper CI
Sustainable Manufacturing ↔ Industry 4.0 Readiness	0.966	0.946	0.984
Smart Product ↔ Employees	0.956	0.924	0.987
Smart Product ↔ Smart Operations	0.949	0.915	0.979
Smart Operations ↔ Smart Factory	0.910	0.872	0.943
Strategy and Organisation ↔ Industry 4.0 Readiness	0.884	0.817	0.942
Employees ↔ Data-Driven Services	0.086	0.044	0.206

Figure 2 presents the final reflective loadings and the standardised structural paths estimated from the corrected PLS model.

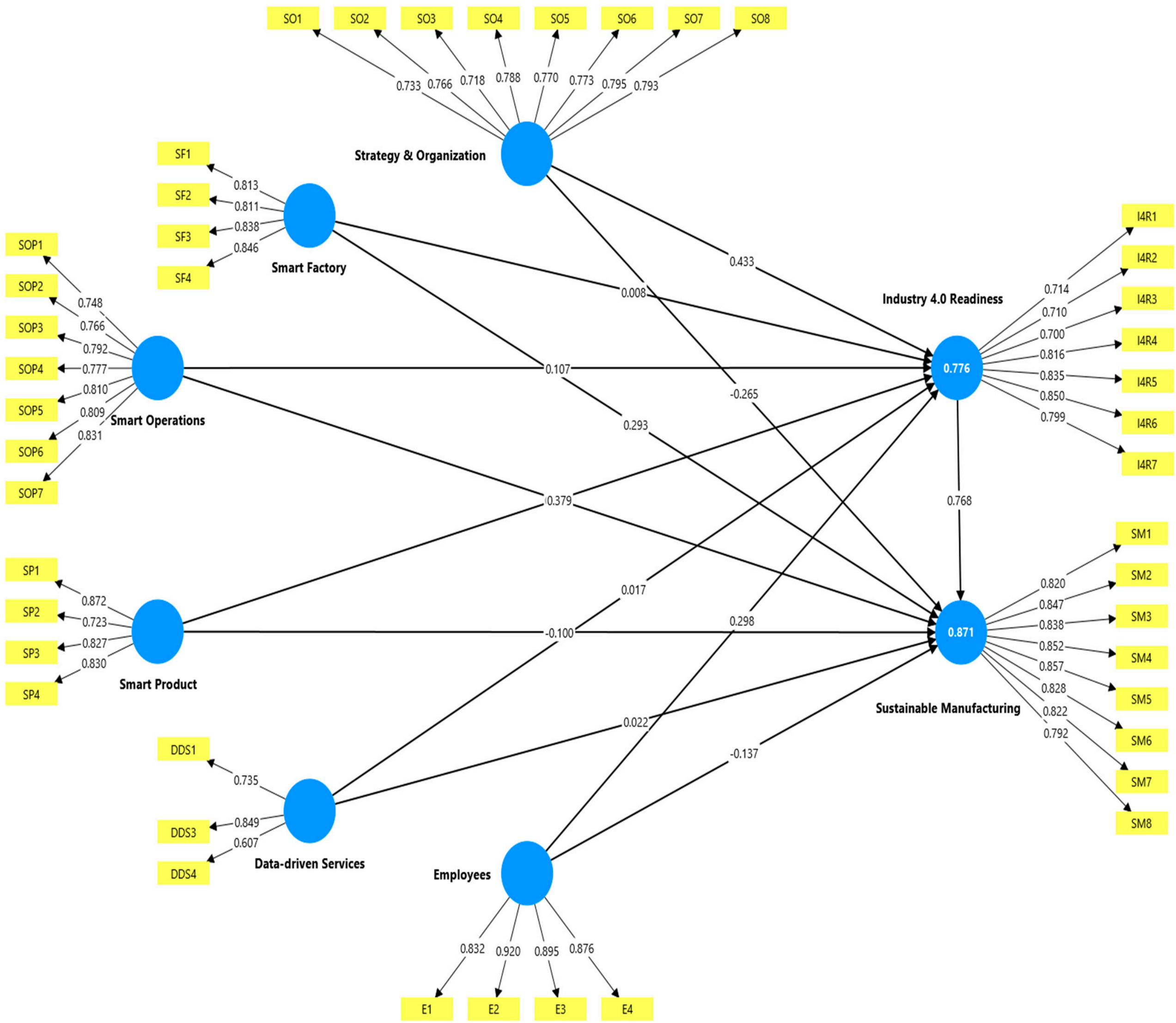

Figure 2. Corrected measurement and structural model (PLS solution).

4.3. Structural Model Assessment

Once measurement adequacy was established, the structural model was tested using collinearity diagnostics, path coefficients, explanatory power, effect sizes, and mediation analysis. The inner VIF values ranged from 1.014 to 6.128. When predicting Industry 4.0 readiness, the highest VIFs were related to smart products, as well as smart operations. This indicates conceptual proximity between operational and product-oriented Industry 4.0 capabilities and instability redundancy. Given that the signs of the coefficients remained unchanged and that the VIF values did not show any strong collinearity, it was assumed that the structural model was interpretable.

The model had high explanatory power. Industry 4.0 readiness exhibited a 0.776 R^2 value and an adjusted R^2 of 0.773, with the six IMPULS dimensions explaining a significant portion of the readiness variance. Sustainable manufacturing generated an R^2 of 0.870 and an adjusted R^2 of 0.868, which indicates very strong explanatory power. Based on standard PLS-SEM norms, these values indicate that the endogenous constructs have significant predictive and explanatory relevance [97].

The model fit indicators also indicated acceptable specification. The SRMR value was 0.078, which is within the generally accepted threshold of 0.08. The NFI value was 0.660, which is not significant and was not exaggerated. The global fit indices in PLS-

SEM are regarded as additional and not conclusive, as the primary focus is on the quality of measurement, explanatory power, predictive relevance, and theoretically meaningful paths [97].

Direct Effects and Hypothesis Testing

The significance of the structural paths was estimated by bootstrapping using 5000 sub-samples as pictorially represented below in Figure 3. The results shown in Table 7 indicate that strategy and organisation was the strongest predictor of Industry 4.0 readiness (β = 0.434, t = 8.441, $p < 0.001$), followed by employees (β = 0.295, t = 8.152, $p < 0.001$), smart products (β = 0.154, t = 3.091, $p = 0.002$), and smart operations (β = 0.108, t = 2.437, $p = 0.015$). These results suggest that strategy alignment and human capacity are more influential in creating readiness than technology possession alone.

Table 7. Structural model results.

Path	*β*	*t*-Value	*p*-Value	Decision
SO → I4R	0.434	8.441	<0.001	Supported
E → I4R	0.295	8.152	<0.001	Supported
SP → I4R	0.154	3.091	0.002	Supported
SOP → I4R	0.108	2.437	0.015	Supported
SF → I4R	0.008	0.182	0.855	Not supported
DDS → I4R	0.017	0.681	0.496	Not supported
I4R → SM	0.757	12.470	<0.001	Supported
SOP → SM	0.337	8.518	<0.001	Supported
SF → SM	0.268	8.086	<0.001	Supported
SP → SM	−0.100	2.387	0.017	Supported (negative)
SO → SM	−0.243	5.120	<0.001	Supported (negative)
E → SM	−0.182	4.996	<0.001	Supported (negative)
DDS → SM	0.020	1.052	0.293	Not supported

By contrast, smart factories had no significant effect on Industry 4.0 readiness (β = 0.008, $t = 0.182$, $p = 0.855$), and data-driven services also showed no significant effect (β = 0.017, $t = 0.681$, $p = 0.496$). This implies that technologies and analytics-based services at the factory level might not necessarily be translated into wider organisational readiness without being anchored by strategies, workforce abilities, and operational integration.

In the case of sustainable manufacturing, Industry 4.0 readiness was found to be the strongest predictor (I4.0 readiness), as it had a positive effect (0.757), *t*-value (12.470), and *p*-value (0.001). Smart operations also had a significant positive effect (β = 0.337, $t = 8.518$, $p < 0.001$), followed by smart factories (β = 0.268, $t = 8.086$, $p < 0.001$). On the other hand, smart products had a direct, strong negative impact on sustainable manufacturing (β = −0.100, $t = 2.387$, $p = 0.017$). This observation implies that smart product projects might not necessarily yield sustainability benefits unless they are integrated into the broader Industry 4.0 readiness capacity. In this regard, product-level intelligence seems to demand organisational readiness prior to its sustainability value being exploited.

Interestingly, strategy and organisation (β = −0.243, t = 5.120, $p < 0.001$) and employees (β = −0.182, t = 4.996, $p < 0.001$) showed significant direct negative effects on sustainable manufacturing. This does not necessarily mean that strategy or employee capabilities negatively affect sustainability. Instead, it implies that strategic and workforce investments can give rise to transitional costs, coordination pressures, or delayed benefits unless they are aligned with Industry 4.0 readiness. In other words, readiness seems to be the state that changes these abilities into sustainability value.

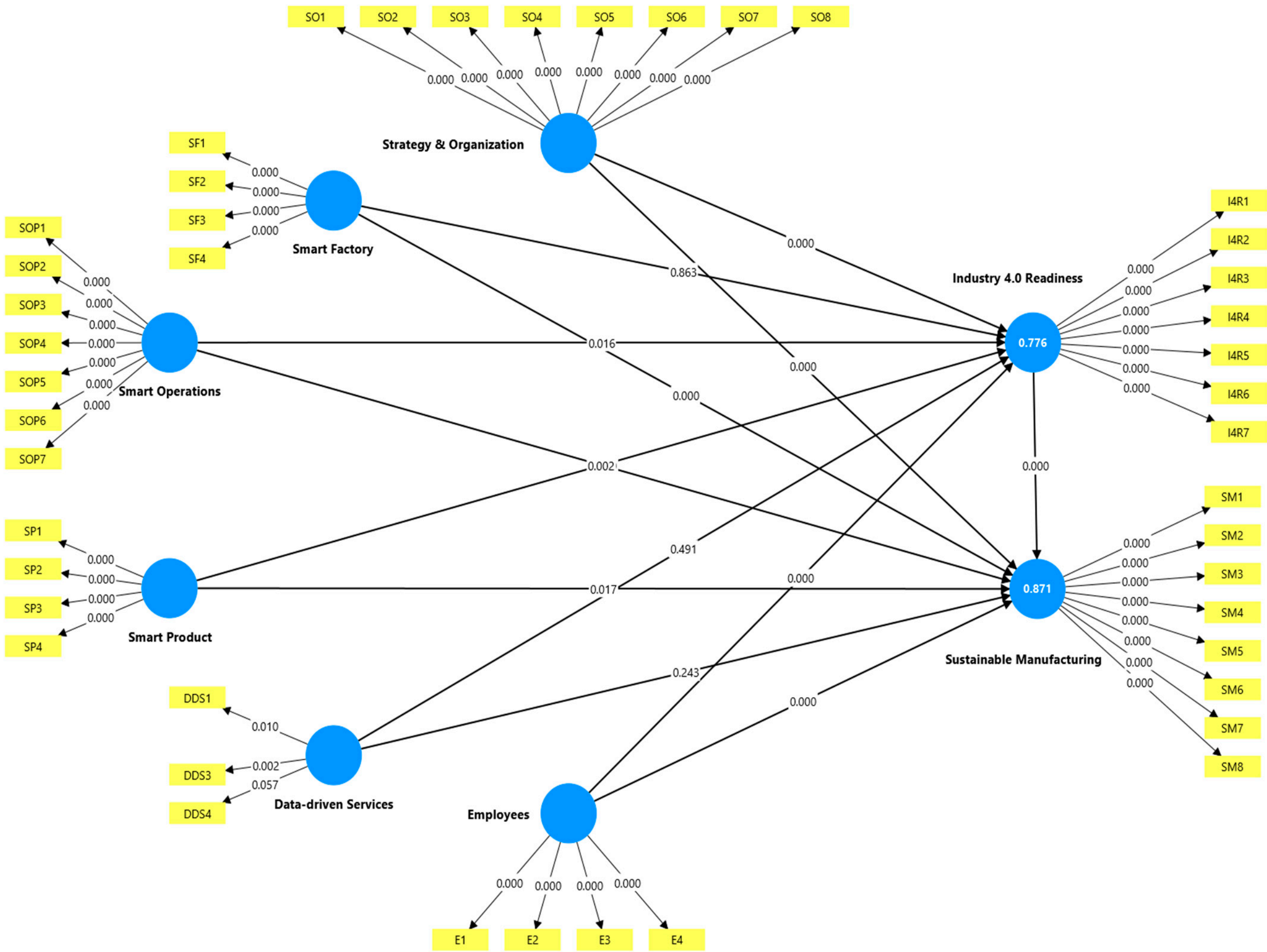

Figure 3. Bootstrapped structural model results. *(The bootstrapped solution confirms the dominant contribution of Industry 4.0 readiness to sustainable manufacturing and the selective significance of the exogenous antecedents.).*

4.4. Effect Size Evaluation

The effect size was measured in terms of f^2 to identify the practical contributions of each predictor. The largest impact on sustainable manufacturing was for Industry 4.0 readiness ($f^2 = 1.004$), which presents a very large practical impact. This affirms the fact that readiness is not a peripheral construct but the explanatory mechanism dominant in the model. The largest impact on Industry 4.0 readiness ($f^2 = 0.251$) was for strategy and organisation, which was moderately to substantially contributing. Smart operations ($f^2 = 0.192$) and smart factories ($f^2 = 0.182$) were also found to have significant impacts on sustainable manufacturing. These results support the idea that sustainable production is not achieved through the isolated application of specific technologies but through the harmonisation of I4.0 readiness, manufacturing capacity, and the digitalisation of factories.

4.5. Mediation Analysis

Bootstrapped indirect effects were used to determine the mediating role of Industry 4.0 readiness. A mediation analysis would be suitable on cases where theory suggests that an independent variable influences an outcome via an intervening mechanism as opposed to through a direct path only. Bootstrapping is suggested to test indirect effects in PLS-SEM since bootstrapping does not assume that the sampling distribution of the mediating effect is normally distributed [113]. The results suggest that Industry 4.0 readiness is an important mediator between strategy and organisation and sustainable manufacturing; employees and sustainable manufacturing; smart operations and sustainable manufacturing; and smart products and sustainable manufacturing. No significant mediation was found for smart factories and data-driven services.

The mediation pattern holds theoretical significance, as reflected in Table 8. Strategy and organisation and employees demonstrated competitive mediation, with their direct effects on sustainable manufacturing being negative and indirect effects through Industry 4.0 readiness being positive. This implies that only when strategic and workforce capabilities are directed through readiness do they become sustainability-enhancing. Smart operations demonstrated bi-directional complementary mediation, with both the direct and indirect effects being positive. Smart products exhibited an indirect-only mediation pattern, which means that smart product capabilities contribute to sustainability mainly by enhancing Industry 4.0.

Table 8. Indirect effects via Industry 4.0 readiness.

Indirect Path	β Indirect	*p*-Value	β Direct	β Total	Type
SO → I4R → SM	0.328	<0.001	−0.243	0.086	Competitive
E → I4R → SM	0.223	<0.001	−0.182	0.042	Competitive
SOP → I4R → SM	0.082	0.024	0.337	0.419	*Partial* complementary
SP → I4R → SM	0.117	0.003	−0.100	0.016	Competitive
SF → I4R → SM	0.006	0.855	0.268	0.274	No mediation
DDS → I4R → SM	0.013	0.504	0.020	0.033	No mediation

Note: SO = Strategy and Organisation; E = Employees; SOP = Smart Operations; SP = Smart Product; SF = Smart Factory; DDS = Data-driven Services; I4R = Industry 4.0 Readiness; SM = Sustainable Manufacturing. Competitive mediation occurs when significant direct and indirect effects have opposite signs; partial complementary mediation occurs when both effects are significant and have the same direction; no mediation indicates a non-significant indirect effect.

In comparison, smart factories had a direct impact on sustainable manufacturing, but not indirectly via readiness. This means that intelligent factory technologies can enhance resource utilisation and performance without necessarily changing the overall organisational state of readiness. Data-driven services did not exhibit any significant direct or indirect impacts, which supports the interpretation that, in the sampled context, analytics-based service capabilities are still relatively underdeveloped.

4.6. Summary of Hypotheses

Table 9 shows that the results offer partial confirmation of the suggested framework. There were four IMPULS dimensions that greatly predicted Industry 4.0 readiness: strategy and organisation, smart operations, smart products, and employees. There was no significant predictability of readiness for smart factory and data-driven services. Sustainable manufacturing was significantly predicted by Industry 4.0 readiness, smart operations, and smart factory. The direct effects of strategy and organisation and employees on sustainable manufacturing were significant but negative, implying the presence of complex transformation dynamics as opposed to simple linear benefit pathways.

Table 9. Summary of hypotheses.

Hypothesis	Relationship	Result
H1	Strategy and Organisation → Industry 4.0 Readiness	Supported
H2	Strategy and Organisation → Sustainable Manufacturing	Supported, negative
H3	Smart Factory → Industry 4.0 Readiness	Not supported
H4	Smart Factory → Sustainable Manufacturing	Supported
H5	Smart Operations → Industry 4.0 Readiness	Supported
H6	Smart Operations → Sustainable Manufacturing	Supported
H7	Smart Product → Industry 4.0 Readiness	Supported
H8	Smart Product → Sustainable Manufacturing	Supported, negative
H9	Data-driven Services → Industry 4.0 Readiness	Not supported
H10	Data-driven Services → Sustainable Manufacturing	Not supported
H11	Employees → Industry 4.0 Readiness	Supported
H12	Employees → Sustainable Manufacturing	Supported, negative
H13	Industry 4.0 Readiness → Sustainable Manufacturing	Supported
H14	Strategy and Organisation → Industry 4.0 Readiness → Sustainable Manufacturing	Supported
H15	Smart Factory → Industry 4.0 Readiness → Sustainable Manufacturing	Not supported
H16	Smart Operations → Industry 4.0 Readiness→ Sustainable Manufacturing	Supported
H17	Smart Product → Industry 4.0 Readiness→ Sustainable Manufacturing	Supported
H18	Data-driven Services → Industry 4.0 Readiness→ Sustainable Manufacturing	Not supported
H19	Employees → Industry 4.0 Readiness→ Sustainable Manufacturing	Supported

5. Conclusions

5.1. Concluding Overview

This study examined how the six IMPULS dimensions shape Industry 4.0 readiness and how, in turn, readiness contributes to sustainable manufacturing within Pakistan's manufacturing sector. The study was positioned against a clear gap in the literature: while Industry 4.0 has been widely linked to productivity, automation, and sustainability, less is known about how organisational and technological capabilities are converted into sustainability outcomes in emerging economy manufacturing contexts. The empirical model therefore tested the direct effects of strategy and organisation, smart factories, smart operations, smart products, data-driven services, and employees on Industry 4.0 readiness and sustainable manufacturing, as well as the mediating role of readiness.

The findings show that sustainable manufacturing is not simply a consequence of adopting digital technologies. Rather, sustainability gains depend on whether firms develop a coherent readiness capability that connects strategic direction, workforce competence, operational integration, and technology use. This supports contemporary PLS-SEM-based Industry 4.0 research, where explanatory strength is judged not only through significant paths but also through model quality, effect sizes, and theoretically meaningful indirect mechanisms [97,113].

5.2. Synthesis of the Principal Findings

The initial significant finding is that the Industry 4.0 readiness was found to be the most important explanatory factor in the model. The six IMPULS dimensions explained a significant percentage of the variance in Industry 4.0 readiness (R^2 = 0.776), and the entire model explained an even greater percentage of the variance in sustainable manufacturing (R^2 = 0.870). These values imply that the model has strong explanatory power and that it provides a strong account of the relationship between readiness and sustainability in Pakistani manufacturing companies.

Second, strategy and organisation had the greatest influence on Industry 4.0 readiness, followed by employees, smart products, and smart operations. This implies that readiness is conditioned not by individual technology ownership but rather by the alignment of strategies, the commitment of leaders, the ability of the workforce to execute it, and the coordination of operations. In contrast, smart factories and data-driven services failed to serve as significant predictors of readiness, suggesting that technology infrastructure and analytics-based services might remain disconnected unless they are embedded in broader organisational transformation.

Third, Industry 4.0 readiness had the strongest impact on sustainable manufacturing, which was followed by smart operations and smart factories. These findings suggest that sustainability gains are most pronounced when companies have systemic readiness and operationally embedded digital readiness. Nevertheless, strategy and organisation, employees, and smart products had direct, strong negative impacts on sustainable manufacturing. Such results do not necessarily contradict one another. Instead, they imply that strategic initiatives, workforce development, and intelligent product capabilities can initially impose coordination strains, implementation expenses, or operational complexity unless they are funnelled through mature readiness capabilities.

Fourth, the mediation analysis proves that Industry 4.0 readiness demonstrates a selective, yet critical, mediating effect. It greatly mediated the impacts of strategy and organisation, employees, smart operations, and smart products on sustainable manufacturing. Specifically, all four elements (strategy and organisation, employees, and smart products) followed a competitive mediation pattern wherein the negative direct effects were mediated by the positive indirect effects through readiness.

5.3. Theoretical Contributions

This paper contributes to the literature on Industry 4.0 and sustainable manufacturing in three ways. First, it expands the IMPULS framework beyond descriptive assessments of readiness. In this way, the study responds to the demand for more rigorous modelling of Industry 4.0 readiness, using validated structural methods rather than maturity profiling alone.

Second, the research contributes to work on sustainable manufacturing by showing that the correlation between digital transformation and sustainability is not always direct. The adverse direct impacts of strategy and organisation, employees, and intelligent products are that short-term adjustment costs may outweigh the long-term benefits of sustainability. This observation counters the belief that every Industry 4.0 capability inherently enhances sustainability.

Thirdly, the research provides empirical evidence supporting the theoretical integration of the technology–organisation–environment (TOE) framework, the resource-based view, and dynamic capabilities theory. The results suggest that readiness can be a dynamic capability whereby firms can coordinate technological resources, organisational structures, workforce capabilities, and operational routines to support sustainability. The application of the HTMT, reliability test, bootstrapped paths, and mediation analysis also enhances the validity of such theoretical statements, as both discriminant and indirect effects are necessary in the assessment of a complex latent variable model [111,113].

5.4. Practical and Policy Implications

The results imply that investment in Industry 4.0 technologies should be supported by conscious preparation for readiness. Companies cannot look forward to the benefits of sustainable manufacturing simply because they have installed smart factory systems or created smart products or they have gathered operational data. Rather, prior to the realisation of sustainability outcomes, managers must align their digital strategies, workforce training, process redesign, and operational integration.

The findings also indicate that smart operations and smart factory capabilities are of significant importance to sustainable manufacturing. Companies should thus focus on technologies and practices to enhance process visibility, resource efficiency, production control, and waste reduction. Nevertheless, the limited potential of data-driven services implies that not all firms may have the analytical culture, infrastructure, or service-oriented business model necessary to transform data into sustainability value. At the policy level, the findings are relevant to Pakistan's wider industrial digitalisation agenda. The results suggest that policymakers should rank technology adoption incentives, digital readiness support, workforce upskilling, and industry–academia collaboration to aid manufacturing firms in moving from fragmented automation toward coordinated Industry 4.0 transformation.

For policymakers, the paper emphasises the need to facilitate the manufacturing sector in Pakistan by providing capability development programmes, digital skills programmes, technology transfer programmes, and sector-specific readiness assessment instruments. The support of policy should go beyond the general digitalisation discourse and include efforts to assist firms in developing the organisational environment necessary to implement Industry 4.0. In future studies of digital manufacturing, predictive assessment and model validation should also become routine tasks, as recommended in the current PLS-SEM guidelines [110].

5.5. Limitations and Directions for Future Research

Despite its contributions, the study has several limitations. First, the cross-sectional design limits the ability to provide a causal interpretation over time. This can be achieved through longitudinal research, which would help in determining whether the direct negative effects of strategy, employees, and smart products decrease with the accumulation of experience in implementation. Second, the authors used self-reported survey data, which could be susceptible to perceptual bias, although common method bias diagnostics were used. Third, although the sample was representative of manufacturing industries in Pakistan, the results are limited to Pakistan and need to be replicated in other emerging and developed economies.

Future studies are recommended to explore contextual moderators, including firm size, ownership, export orientation, automation maturity, and supply chain integration. The data-driven services construct should also be refined in future work to identify more context-sensitive measurements of the construct in emerging manufacturing conditions, where its less reliable and non-significant effects are more pronounced. Lastly, future research should integrate PLSpredict or similar out-of-sample predictive methods to allow claims about the predictive relevance of the model, instead of focusing on the explanatory fit, because models required to provide predictions as well.

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