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Pathways and Countermeasures for Digital-Lean Synergy Driving Technological Innovation in Manufacturing: A Multi Case Study of Chinese Enterprises

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Abstract: As the world's manufacturing sector advances in the direction of digital transformation and intelligence, neither isolated application of new technologies nor stand-alone application of lean management has achieved the goal of continuous technological progress in manufacturing. As a result, both universities and enterprises have begun to study the synergy of digitization and Lean management. Based on the theory of lean production, digital transformation and the Lean Smart Manufacturing framework, this paper will take some representative Chinese manufacturing enterprises as case studies to investigate the internal mechanisms and paths of digital transformation and lean management in the promotion of technological innovation, such as Baowu Steel Group, Midea Group, Zhangzhou Hongfa (Relay), Yonggang Group and HLA (Heilan Home) Supply Chain. From the above results, it can be seen that "lean first, digitalize second, synergies third" is a feasible path for Chinese manufacturers; that is to say, the lean system will provide process standardization and a data foundation for digitization, and digital technology can be employed to monitor the tools of lean in real-time and optimize them intelligently. The new ideas for products, processes and business models will be advanced through "waste reduction - data empowerment - value co-creation" by means of digital-lean synergy, and to achieve this, a full-coverage safeguard system covering organizational reform, cross-departmental talent cultivation and data governance needs to be established. This paper will present some local experimental data on the discourse of Lean 4.0 and Digital Lean in China and Provides some ways for the manufacturing enterprise to achieve high-quality technological innovation.

Keywords: Digital Transformation; Lean Production; Manufacturing Technological Innovation; Multi-Case Study

1. Introduction

1.1 Research Background and Problem Formulation

Digitization and intelligentization are reshaping the form of manufacturing around the world. The national strategy of Germany is "Industry 4.0", the United States has released the "Advanced Manufacturing Partnership", and China has launched the "Strategy for Building a Manufacturing Powerhouse"; all aim to spur the new wave of information technology and manufacturing integration to change the rules of global industrial competition through technological revolution.

However, based on the actual situation of Chinese manufacturing, two problems have arisen. On the one hand, enterprises that rush to digitize invest heavily in MES, ERP and IoT platforms, but they have created many "digital silos" and their investment returns are low because the on-site processes have not been standardised and various forms of waste have not been systematically eliminated. At the same time, although the enterprise has long been constructing a lean management system and created good 5S, Kanban, value-stream analysis, etc., these traditional lean tools are unable to meet the needs of high-mix, low-volume production, frequent changes in the supply chain, etc., and cannot provide information for timely decision-making. Both still have problems; the large investment in digitization has not yielded results, and the small improvement has reached a ceiling. Therefore, it has not been determined whether digitization and lean management will work together or be in opposition, and more research is needed to figure out how to use both optimally.

To address this problem, Wu and Liu [1] put forward the concept of "Lean Smart Manufacturing" and believed that smart manufacturing should be based on the continuous improvement of the Physical System, that is, the physical layer within the cybersex-physical system architecture; to achieve customer value creation, a two-stage process of lean refinement, digitization, and then intelligentization is needed. Mao [2] believes that the traditional lean and data-driven ways of working in automotive parts enterprises are not compatible and need to be jointly innovated in terms of technology, organization and processes. Although the above studies have explored the link between digitization and lean management from all sides, most current research focuses on either the application of lean management or digital technology separately; a comprehensive multi-case study in China that examines the reasons for and ways to promote technological innovation through the synergy of the two has not been carried out. Based on this research gap, the three main problems to be studied in this paper are: First, how does the combination of digitization and lean management promote technological innovation in manufacturing, and what are the underlying reasons? Second, what are the viable paths and main factors for success in China's enterprises going digital-lean. Third, what areas should the government and the management system focus on supporting to promote this synergy?

1.2 Research Significance

The theoretical value of this paper is to integrate the theories of lean production, the resource-based view and the theory of digital technology enablement organically, provide empirical data and theoretical expansion for the international academic discussion on "Lean 4.0" and "Digital Lean", and thus add new connotations and boundaries to this interdisciplinary field in our country. In practice, by collecting and analyzing the good cases of some leading Chinese enterprises systematically, this paper will provide an implementable and generalizable synergistic path and method that can offer specific operating direction for manufacturing enterprises in the process of digitization and help them achieve the goals of technological innovation and cost reduction through management-technology integration.

1.3 Research Methodology and Case Selection

According to the Yin [3] principle of case study design, which is suitable for addressing explanatory research questions about how and why, this paper will use an exploratory multi-case research method and select the cases accordingly. In the process of case selection, we followed the rule of theoretical sampling and finally selected five representative Chinese enterprises from different industrial sub-sectors that have implemented digital-lean management: Baowu Steel Group (now under the China Baowu Steel Group) in the steel industry, Midea Group in the home appliance industry, Zhangzhou Hongfa in the electronic components industry, Yonggang Group in the steel industry, and HLA at the end of the textile and apparel supply chain. The five enterprises are divided into two groups of process and discrete manufacturing models, and there are also various differences in the start time of lean management, the entry point for digitization, and the degree of synergy between the two; therefore, they are suitable for cross-case analysis. As for the origin of this data, it has been obtained through several ways in this study, such as the corporate official website, annual reports, industry white papers, published academic papers and case-sharing materials to ensure the reliability and validity of the data by triangulating.

2. Literature Review and Theoretical Framework

2.1 Lean Production Theory and Its Digital Evolution

Lean production, as a management philosophy originating from the Toyota Production System (TPS), is based on the "thorough elimination of waste" and "continuous improvement (Kaizen)," achieving high-efficiency, low-cost production operations through an integrated toolkit encompassing just-in-time (JIT), Jidoka (automation), standardized work, and kanban management. The strength of traditional lean management lies in its capacity to stabilize processes, surface problems, and continuously elevate operational performance through organization-wide improvement activities. However, it also manifests a pronounced shortcoming: excessive reliance on human experience and retrospective analysis. When confronted with production scenarios characterized by high-frequency variability, complex coupling, and multivariate interactions, traditional lean approaches frequently fail to capture root causes in a timely manner and mount rapid responses. It is precisely this limitation that has opened the space for the intervention of digital technologies.

In recent years, the international academic community has engaged in vigorous debate regarding the relationship between Industry 4.0 and lean management. Aziana, Mamat, Ibrahim, et al. [4] explicitly pointed out that Industry 4.0 and lean management are not mutually exclusive but rather can be mutually reinforcing: lean management provides the standardization and data collection foundation for digitization, while digital technologies (such as IoT, big data, and AI) enable real-time and intelligent upgrades of traditional lean tools (such as value stream mapping, and on systems, and total productive maintenance). This assertion holds significant guiding implications for understanding the sequential ordering and synergistic logic of digitization and lean management.

2.2 Digital Transformation and Technological Innovation in Manufacturing

In terms of the connotation of digital transformation in manufacturing, next-generation information technology can be used to build a complete closed-loop system for data collection, transmission, storage, processing and feedback; at various levels of the enterprise and in the upstream and downstream supply chain, data barriers can be broken down, overall operating efficiency can be improved, and ultimately a digital economy system can be constructed. Based on the above definitions, the paths of digitization for promoting technological innovation can be roughly classified into three types: First, upgrading the IT system can be promoted to enhance the adaptability of enterprises to changes in the market and consumer demand under all weather conditions and improve the speed of response; Second, through distillation, optimization and intelligentization of the production process, substantial increases in production efficiency and reductions in resource waste can be achieved; Third, digitization can extend the value chain and expand the scope of traditional manufacturing by adding new areas of service, such as service factories for manufacturing and predictive maintenance.

However, if digital transformation is carried out without the direction of lean thinking, it will be prone to the problem of “technology for technology’s sake”, fail to meet the actual needs of customers, and thus yield poor investment returns. In other words, although a company has a high-tech digital system, if it has not been reformed in the direction of Lean, it will not work optimally.

2.3 Theoretical Framework for Digital-Lean Synergistic Innovation

Based on the literature review above, the theoretical foundation for the following case studies in this paper will be the “Foundation-Entanglement-Output” synergistic drive model. The components of the lean foundation layer are standardization of work, optimization of the value stream, 5S management, total productive maintenance and a culture of continuous improvement; its first task is to stabilize the process, collect data, set clear improvement goals for the whole system, etc. The Digital Enablement Layer consists of IoT sensing, integration of MES/ERP/PLM systems, a big data platform and BI/AI tools, etc.; In the future, it is hoped that timely waste visualization and early warning of abnormal situations, intelligent optimization of process parameters, and organized accumulation of knowledge can be achieved. Together, both sides are making an effort to deal with the problem of waste; that is to say, by reducing waste in Lean and using data-driven decision support tools enabled by digitization, it has been realized that precision can be increased and innovation promoted. Finally, through the combination of the above factors, some new-era products and improved production methods have been formed, thereby enhancing product quality and shortening the time to introduce new products; at the same time, the overall equipment efficiency has increased, and energy consumption has been reduced; new business models such as the service and customization of manufacturing have also appeared. Naturally, the synergistic effect will not be realized in a vacuum; therefore, context such as the scale of the company, the characteristics of the industry and its data governance ability will affect the results.

3. Research Design and Case Description

3.1 Data Collection and Analysis

For the purpose of data collection in this study, secondary sources were used as the main basis; that is to say, corporate official websites, listed company annual reports, industry white papers, professional reports available on the e-works digital enterprise network, and published academic papers were systematically coded and analyzed. All the cases in the analysis were organized and summarized according to the four components systematically in the analysis process, and generalizing rules were extracted, and at the same time, the development path of each company was reconstructed accurately.

3.2 Baowu Steel Group—Predictive Maintenance and AI-Augmented Quality Closed Loop

Nippon Steel began its management system in 1978, and ever since, Baosteel has gradually built a comprehensive lean production system and prepared the foundation for digitization in the following years. In 2010, Baosteel started to carry out its “Digital Baosteel” plan and built a three-tier ERP, MES and PCS information architecture; later, it has promoted the construction of a “lights-out factory” and introduced artificial intelligence technology at the Zhanjiang and Baoshan bases. Many vibration and temperature sensors have been installed on the hot-rolling and cold-rolling equipment at Baowu, machine learning algorithms have been used to predict the remaining useful life of the equipment, and therefore the traditional total productive maintenance has changed from reactive repair and scheduled maintenance to predictive maintenance. According to the company's published information, the plan has reduced unplanned downtime by about 20 per cent. In terms of quality management, Baowu has connected the inspection results of the surface inspection system to process parameters to find defects and their locations accurately, and can even automatically suggest probable causes for the defects, such as abnormal wear in a specific mill stand; thus, it has realized the intelligent application of the Jidoka concept in the Toyota Production System. Digital twin technology has been applied to production scheduling, and a few schedules can be implemented in the virtual environment by the dispatch office; according to the current situation of equipment and materials, delivery time, etc., an optimized plan with minimal transition waste can be developed. Most importantly, the reason why the AI model of Baowu can be applied in actual production is that the company has established a lean standardized work and anomaly management culture early on; thus, the input data for the model is highly regular. At the same time, front-line operators are willing to be led by the system to achieve the ideal state of "model accuracy and on-site implementation", which is in line with the general trend of AI-driven lean transformation in steel enterprises [5].

3.3 Midea Group—Comprehensive Digital Reconstruction Built on the MBS Foundation

In 2011, Midea Group began its digital transformation and made a radical decision at the time: to increase the scale of low-end capacity and comprehensively implement the “Midea Business System” (MBS). The production system has incorporated the main ideas of the Toyota Production System and Six Sigma management to conduct value-stream analysis and production-line Takt time adjustment in an orderly manner to eliminate all types of waste and improve operating efficiency. After some initial results from the lean management, Midea released the “632 Strategy” in 2012 to carry out all-round restructuring of the IT system, build six operating platforms, three management platforms and two portal systems, unify data standards and business processes across the group, etc. Based on the above foundation, Midea has been continuously increasing investment in automation and MES systems to achieve full transparency of the production process, intelligent logistics distribution, data-driven business decision-making, etc. With the help of an Advanced Planning and Scheduling (APS) system, backward deduction according to Just-in-Time (JIT) principles can be used to support the efficient operation of high-mix, low-volume flexible production mode, and at the same time, a C2M modular platform is being employed to lead the way in mass personalized customization services for home appliances. In the last decade or so, Midea has made significant changes; its total number of employees has dropped from 196,000 to about 93,000, but its revenue remains relatively the same, and both profit and operating cash flow have been rising. Based on the above results, it can be concluded that although lean management has reduced waste and released resources, the impact of digital technology is quite large in those four aspects and has also promoted the formation of a new business model for mass personalize customization of major home appliances [6].

3.4 Zhangzhou Hongfa—Strictly Following "Lean First, Digitalize Second"

Zhangzhou Hongfa is an electronic components company that makes relays and, as such, has been practicing "lean first, digitalize second" in its digitization and leanness. In 2011, the company started to implement lean management, and in the following years, all kinds of activities related to it have been systematically carried out, such as value stream mapping, production line balancing, SMED (Single-Minute Exchange of Die) and total productive maintenance; only in 2020 was it officially launched that the digital transformation had reached the "comprehensive improvement stage" for the production line. In terms of implementation, Zhangzhou Hongfa has divided it into three stages: In the first stage, it focused on business process re-engineering, employed the ECRS (Eliminate, Combine, Rearrange, Simplify) method to optimize the operating workflow, established standard work instructions, and strengthened the anomaly response mechanism; In the second stage, the previous manual reporting system was organized through the addition of MES and ERP, the entire business process was fully digitized, and in the third stage, a Fanruan BI-based data platform has been built, data channels among MES, WMS, and ERP have been opened, a visual management cockpit for key indicators has been constructed, and at this time, the automatic data collection rate of these indicators reached 82%. As a result of the above measures, Zhangzhou Hongfa has achieved automatic shortage alerts, raised the order delivery rate to 99.3%, and increased the first-pass delivery qualification rate from 97.89% to 100%. The enterprise mentioned in its experience sharing explicitly said: "Enterprises that have not begun lean production work are advised not to start digitization", which is in line with the academic view that "lean is a prerequisite for digitization, and digitization is the lever to advance lean" [7].

3.5 Yonggang Group—"Lean 6+1" and Digital 5S Platform

Yonggang Group is a steel enterprise that has been building a different road for the combination of lean management and digitization. As shown in, they have constructed an entire-system operating system called "Lean 6+1", which consists of the following six main components: performance management, standardization of operations, workstation-level improvement proposals, lean on-site practice, lean projects and foundational modules, as well as strong support. The first is that the whole plant has been turned into a digital version of traditional 5S management, a one-star to three-star certification system has been established, and these rating results directly affect employees' performance evaluations. Second, an "On-site 5S Management Online System" has been built using the Lark (Feishu) low-code platform to have employees report problems in their work areas by scanning mobile QR codes; subsequently, work orders will be automatically released to the person in charge, closed-loop tracking will be carried out after the rectification is completed, and even AI-assisted diagnosis will be used to improve the accuracy of problem identification. Third, the 5S scores have been linked with other indicators, such as equipment failure rates and quality defect rates, to identify urgent areas for improvement and weak links in the process. As a result, the improvements have been significant; per ca-pita improvement proposals have risen from 0.5 to 12.17, the rectification rate is now over 99%, and the annual cost saving is more than 50 million yuan. Yonggang's experience shows that digital technology can make small improvements in Lean quantifiable, sustainable and horizontally scalable, so it does not have the problem of traditional Lean improvement initiatives turning into campaign-style improvements [8].

3.6 HLA—Digital Supply Chain Pulling Upstream Lean

The HLA case is different from the previous four; it shows that digital-lean synergy at the industrial chain level can promote business model and service innovation. HLA is a clothing company that concentrates on brand operations and platform integration, so it has started to use big data analysis in the front end to understand changes in consumer fashion and consumption trends more accurately, and at the same time built a high-degree digitized supply chain management platform on the back end. The real-time data from the retail store points of sale is sent to the head office, and according to this data, the system will promptly adjust the replenishment plan to ensure the availability of goods and reduce safety stock. At the same time, a joint receiving and dispatching management, logistics tracking and settlement control platform has been established to increase the pressure on upstream suppliers to deliver on time in good condition and promote the implementation of Kanban production and standardized packaging by these suppliers. The above arrangement has formed a good cooperative chain of “data-driven demand identification, brand-side lean planning and scheduling, and supplier just-in-time delivery”, which can be considered a typical case of digital-lean synergy at the level of the industrial chain and provides some reference ideas for manufacturing enterprises that want to increase value through servitization transformation [9].

4. Case Analysis and Research Findings

4.1 Mechanisms of Digital-Lean Synergistic Drive on Technological Innovation

Based on a cross-case analysis of the five cases, it has been found that digitization and lean management work together to promote the development of technology in the following three ways.

The first way can be considered to have laid the foundation for “lean standardization →data accessibility→digitally enabled improvement”, and the activities promoted by lean management, such as standardized work, tact time measurement, work-in-progress control and institutionalized equipment inspection, have parametrized and made explicit the production process that was previously vague and based on experience; thus, clear reference points for sensor deployment locations and data dictionary definitions have been provided. Both Zhangzhou Hongfa and Yonggang have shown that, after creating standard operating procedures and performing value stream analysis, a company can precisely identify at which stage of the process data needs to be collected, what kinds of data are required, and what problems this data will help solve; thus, the problem of "garbage in, garbage out" can be avoided. Wu and Liu [1], along with other scholars, have shown that continuous improvement of the Physical System is an indispensable prerequisite for the creation of value in cyber-physical systems, and lean refinement must precede intelligentization.

The second is the tool improvement mechanism of “digital real-time sensing→lean tool upgrading→ efficiency leap”; that is to say, the Kanban cards that used to inform workers of material-demand changes in the past were physical cards, value stream maps were static hand-drawn diagrams, total productive maintenance relied on periodic experience inspection, and 5S inspections had to be carried out manually by walking around and scoring. With the introduction of digital technology in recent years, these traditional methods have also been transformed; Kanban has gone digital and is now connected to the MES for automated material demand planning; the old way of drawing value stream maps by hand is gone and flexible digital twin models can show the current situation of bottleneck stations; experience-based TPM has been upgraded to machine learning-based predictive maintenance; and manual 5S checks have been replaced with mobile photography and AI-enabled automatic recognition. The main change brought about by the above upgrades is that the PDCA cycle in lean management has been significantly reduced from weeks or even months to minutes; thus, waiting waste due to information lag has been greatly reduced, and both the speed and accuracy of improvement activities have been improved.

The third way is the innovation-triggering mechanism of “data insight → new knowledge generation→product/process/model innovation”. After a long time of collecting a large amount of production and operation data, deep mining and analysis of this data often reveal previously unknown hidden patterns and correlations, and the generation of new knowledge can motivate innovation in products, processes, and business models, etc. Midea has used analysis of all-process data to learn that consumers are looking for personalized home appliances, so it has developed customisable product lines; this is a typical case of product innovation. Baowu has employed artificial intelligence to examine the interconnections among all elements of production and product quality to optimsise its production plan and drive change in the manufacturing process. Big data is now being used at HLA to adjust the rules of collaboration among various parties to promote the interests of consumers. At present, “data-driven business” is being referred to as the new level of innovation that has reached a high state of digital-lean synergy.

4.2 Pathway Model for Digital-Lean Synergistic Drive on Technological Innovation

Through comparison of the development time and level of the five cases, this paper presents a model of three stages in development. The first stage is the Lean Foundation Stage; at this time, the enterprise will focus on value stream analysis, systematically identify and eliminate the seven wastes in the production process, build an initial management system that includes standardized work, 5S management, total productive maintenance and kanban pull, and at the same time cultivate a continuous improvement culture and improvement proposal system. The results of this stage are a good sense of process stability, a clear idea of the data, and a goal for improvement. The second stage is the Digital Enablement Stage, and at this time, enterprises start to use equipment networking and IoT sensing systems in their main production processes, construct information systems such as MES, SCADA and WMS, and link all sections of their business data from ERP, PLM, MES, etc., to build a united coding system. At this time, show the current production situation; if there are any problems, automatically send an alarm notification, and at the same time, construct a database of historical analysis. The third stage is the stage of synergistic deepening and innovation-driven development; that is to say, with the application of Business Intelligence (BI) and big data analysis tools, hidden correlations and patterns in the data can be discovered, AI models are employed for specific purposes such as predictive maintenance, intelligent scheduling and visual quality inspection, digital twin technology is used for simulation-based optimization, and cross-enterprise strategic co-creation platforms involving suppliers and customers in a collaborative innovation ecosystem are being built one by one. The results of the above steps will provide a reasonable direction for the continuous development of products, processes and business models, and will also enhance the overall adaptability and innovative capacity of the company.

4.3 Critical Success Factors and Barrier Factors

In the construction of critical success factors, some components have stood out in all the above cases. First of all, there has been continuous support from the top leadership at both Midea and Baowu for this digital transformation initiative over the past decade or so, with the chairman or CEO leading the charge; without such a long-term strategic direction, there would be no change. Second, in terms of the achievement of lean maturity: Zhangzhou Hongfa did not begin digitization until its production line reached the “all-round improvement stage”; thus, it was a cautious attitude to ensure that the digital investment was based on sound management. Thirdly, proactive data governance: At the beginning of the project, all the successful enterprises took various steps to standardize material codes, equipment codes and process parameters in order to eliminate obstacles to the next system integration. Fourthly, cultivation of cross-functional talent: Yonggang established its own “data artisans” programme to train a group of front-line specialists who are good at both shop-floor operations and data analysis; these people then served as the link between the lean shop floor and the digital world. Fifthly, the plan is to pilot and then scale up: Midea started with one plant for its 632 Strategy, showed good returns on investment, and has been gradually extended to other factories to reduce risk.

At the same time, we identified some main reasons. The absence of data interfaces on old equipment is a general problem, so companies have to pay extra for sensor upgrades to add the new Digital Technology. The second problem is that the departments do not share data, and due to their own interests, they are unwilling to do so, so an organization change is needed to reform the way benefits are distributed. Resistance by front-line staff to the new digital tools also needs to be dealt with proactively; regular training will be organized to enhance their sense of responsibility and the spirit of continuous improvement in putting forward suggestions. Finally, due to the demands for short-term financial results, management has repeatedly reduced the budget for lean digitization; it is a serious problem at the top level of the company how to balance long-term strategic advantages with immediate financial performance.

5. Countermeasures and Recommendations

5.1 Enterprise Level

First of all, the first recommendation for manufacturing enterprises that wish to promote digital-lean synergy is to do so in an orderly manner: build a "lean foundation - digital enablement - synergistic innovation" system, and do not be prompted by the desire for a leapfrog to start smart factory projects directly without first establishing this solid lean foundation. Enterprises can adopt the operating model of Zhangzhou Hongfa, carry out a value-stream analysis to find out why there is waste, and then take the main direction of digital intervention from this analysis; thus, some immediate results and experience will be obtained for later large-scale application. In terms of data governance, a special group of data stewards should be established in the company to unify the coding norms for master data, gradually open data channels among MES, ERP, PLM and SCM systems, and build a lightweight data platform or BI platform according to the size and needs of the company.

At the level of organization and talent, it is proposed that cross-functional digital-lean promotion offices be established under the joint leadership of representatives from production, industrial engineering, information technology and quality management; at the same time, a tiered training program should be implemented, which includes improving the sense of strategy for senior management, learning data analysis and value chain restructuring skills for middle managers, and getting familiar with the use of digital tools and how to put forward improvement suggestions for front-line staff. In addition to the conventional indicators of total factor productivity and per ca-pita output value for performance evaluation, the results of synergistic innovation should also be included; for example, “digitization rate of improvement proposals”, “proportion of data-driven decisions” and “reduction rate of new product development cycle” can be added.

In the deployment of AI applications, give priority to those that can directly help achieve the goal of lean production; that is to say, predictive maintenance for the purpose of zero failure, visual quality inspection with the objective of no defects, and intelligent scheduling with the aim of one-piece flow can be released to win the support of front-line staff.

5.2 Industry and Cluster Level

At the level of the industry and industrial cluster, there is a strong role for demonstration and catalysis by leading enterprises. Large-scale enterprises, such as Baowu and Midea, can explore the idea of building industrial Internet platforms to provide upstream and downstream small and medium-sized enterprises (SMEs) with digital inclusion knowledge and tools for the promotion of synergistic upgrading of the entire supply chain, and the model of HLA is a good reference. The industry association can lead the development of “Implementation Guidelines for Digital-Lean Integration in Discrete and Process Manufacturing” and work with the 5S star-rated work zone certification in Yonggang to create a standardization system that can offer optimization directions and reference bases for enterprises. At the industry level, a case-sharing platform and knowledge base can also be established to reduce the learning cost and trial-and-error risk of small and medium-sized enterprises in their exploration of digital-lean.

6. Conclusion and Outlook

6.1 Research Conclusions

Based on the above many cases of comparison, this paper has reached the following three conclusions. First of all, digitization and lean management are not contradictory but rather cooperate with each other; that is to say, lean emphasizes reducing waste, standardizing processes and fostering a culture of continuous improvement; at the same time, digitization provides real-time sensing, data integration and intelligent optimization to help achieve the three paths of manufacturing technological innovation mentioned above: building a foundation, expanding tools and stimulating innovation. Second, based on the actual experience of representative Chinese enterprises, it has been found that the three-stage evolutionary path of “lean refinement first, digitization second, synergistic co-creation third” has been achieved, and this is supported by both the two-stage architecture of Lean Smart Manufacturing and the phased pattern of traditional industrial digitization; therefore, it is applicable and effective in the Chinese context. Thirdly, in order to achieve the success of synergistic drive, continuous support from top management is needed, a certain level of lean maturity should be reached, proactive data governance needs to be established, organised cross-functional talent development and motivation systems should be built, and so on.

6.2 Theoretical Contributions

The above is the theoretical contribution of this paper. It is one of the first studies in China to have investigated the process mechanisms and stage models of the digital-lean synergistic driving of technological innovation based on multiple manufacturing cases systematically, intelligentization the Lean Smart Manufacturing concept from an abstract theoretical framework into observable and analyzable practice paths. This solves the problems in the previous literature; that is to say, to date, most have been based on conceptual architecture deduction or single-industry empirical studies, and they also add local Chinese evidence to the international academic discussion of “Lean 4.0” and “Digital Lean”.

6.3 Limitations and Future Directions

There will also be some shortcomings in this study. Due to time and resources, secondary data analysis has been used in this paper; therefore, we have not been able to conduct first-hand interview coding and validation with the representative case enterprises, and the depth and reliability of the results are relatively limited. In the future, more research will be carried out in the following directions: First, a large number of detailed primary data will be collected through semi-structured interviews and participatory observation at typical case enterprises; Second, quantitative survey instruments will be developed to statistically test the moderating-mediation model of “lean foundation - digitization maturity - innovation performance”; Third, group comparisons will be made according to industry attributes (discrete vs. process manufacturing) and enterprise size (large enterprises vs. Small and medium-sized enterprises have many ways of cooperation in different situations, and fourthly, they are constantly paying attention to new forms and trends of “Lean 4.0” through close cooperation with artificial intelligence technology to provide forward-looking theoretical support for continuous manufacturing innovation.

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