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Interaction and Improvement Strategies Between Science and Technology Service Industry, Human Capital, and Innovation Performance of Intelligent Manufacturing Enterprises

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Abstract: Against the backdrop of the deep integration of the knowledge economy and intelligent manufacturing, innovation has become the key for enterprises to build core competitiveness. As a crucial link connecting technological innovation and industrial application, the science and technology service industry plays an important supporting role in enhancing enterprises' innovation performance. This study focuses on intelligent manufacturing enterprises, systematically exploring the internal mechanism through which the science and technology service industry affects enterprises' innovation performance via the mediating role of human capital. Combined with the actual development of the intelligent manufacturing industry, it proposes multi-level and systematic improvement strategies from the aspects of optimizing the supply of science and technology services, enhancing the effectiveness of human capital, and improving the innovation ecosystem, providing theoretical basis and practical reference for promoting the high-quality development of intelligent manufacturing enterprises.

Keywords: Science and technology service industry; Intelligent manufacturing; Human capital; Innovation performance

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1. Introduction

The intelligent transformation and upgrading of the manufacturing industry has become a strategic focus for enhancing national industrial competitiveness and economic resilience. In the process of moving towards the middle and high ends of the global value chain, China's intelligent manufacturing enterprises still face challenges such as difficulties in breaking through key core technologies, low conversion rates of innovation achievements, and insufficient supply of high-end talents. Against this background, the science and technology service industry, with its characteristics of knowledge intensity, value-added, and radiating driving force, provides intelligent

manufacturing enterprises with professional services such as R&D design, technology transfer, entrepreneurship incubation, inspection and testing, and technological consulting. It has become an important external force to make up for enterprises' innovation shortcomings and improve innovation performance. The promotion effect of the science and technology service industry on enterprises' innovation performance does not occur directly but is achieved by influencing enterprises' internal capabilities [1–3]. Existing studies mostly focus on exploring the relationship between the science and technology service industry and enterprises' innovation performance, or the impact of human capital on enterprises' innovation performance, lacking systematic and integrated research on the transmission chain of "science and technology service industry-human capital-enterprise innovation performance" [4–9]. The research on the intermediate mechanism of how the science and technology service industry specifically affects enterprises' human capital and then drives innovation is not in-depth [10]. This study aims to construct and verify an integrated theoretical model, reveal how the science and technology service industry empowers human capital to drive the improvement of innovation performance of intelligent manufacturing enterprises, and put forward operable strategic suggestions.

2. Analysis of the interaction between science and technology service industry, human capital, and innovation performance of intelligent manufacturing enterprises

2.1. Impact of the science and technology service industry on human capital

The composition of human capital includes not only individuals' knowledge reserves and skill levels but also their collaborative networks, innovation willingness, and comprehensive problem-solving abilities. The science and technology service industry acts on all aspects of human capital through multi-level and multi-dimensional service supply.

2.1.1. Knowledge transmission and skill upgrading: Strengthening the intellectual foundation of human capital

Knowledge supply and skill improvement by the science and technology service industry lay a solid foundation for human capital. The science and technology service industry is an important "transmission belt" for cutting-edge knowledge and technical skills. For instance:

(1) Technical training services in the field of intelligent manufacturing can directly transfer the latest industrial software operation, intelligent equipment maintenance, data analysis algorithms and other skills to enterprise engineers and technical workers, shortening the enterprise's own learning curve;

(2) Expert consulting and technical services, such as when enterprises implement ERP, MES, or digital twin systems, experts from science and technology service institutions not only solve specific technical problems but also subtly improve the enterprise team's system planning and problem-solving capabilities through the "learning-by-doing" model;

(3) Scientific and technological information and market analysis services provide R&D and management personnel with in-depth insights into technical routes, patent layouts, and market demands, broadening their knowledge horizons and enhancing their information-based decision-making capabilities. This continuous injection of knowledge and skills enables the continuous update and deepening of the knowledge structure of enterprise human capital, laying a solid intellectual foundation for innovation activities.

2.1.2. Collaborative networks and platform building: Expanding the social dimension of human capital

Collaborative platforms and network construction by the science and technology service industry expand the social dimension of human capital. Innovation often arises from the intersection and collision of ideas. The science and technology service industry plays an irreplaceable "connector" role in building cross-organizational collaborative platforms and innovation networks. On one hand, science and technology service institutions create opportunities for face-to-face communication between enterprise employees and university professors, experts from research institutes, peers in the upstream and downstream of the industrial chain, and even cross-field entrepreneurs by building industry-university-research cooperation platforms, organizing technical salons, and holding innovation challenges. This interaction breaks organizational boundaries and promotes the flow and sharing of tacit knowledge. On the other hand, the collaborative R&D, technology transfer and other services provided by the science and technology service industry itself require close cooperation between internal enterprise personnel and external service teams. In this process, enterprise employees not only acquire new technologies but also learn how to manage and coordinate external innovation resources, improving their abilities of open collaboration and network integration. The social network dimension of human capital is expanded, and the breadth of their innovative thinking and channels for obtaining heterogeneous knowledge are also broadened accordingly.

2.1.3. Innovation environment and cultural catalysis: Activating the endogenous potential of human capital

Innovation environment and cultural influence by the science and technology service industry stimulate the inherent potential of human capital. The sustainability of innovation is inseparable from a cultural atmosphere that encourages exploration and tolerates failure. High-quality science and technology services can act as a "catalyst" to help enterprises shape and strengthen such an innovative culture. For large intelligent manufacturing enterprises, innovation management consulting services can help them design a more flexible R&D organizational structure, a more incentive innovation reward system, and a more effective internal maker mechanism, systematically cultivating an innovative environment from the management level. When employees are in an innovative environment supported by high-quality external services and encouraged by internal management mechanisms, their willingness to take risks and conduct original exploration will be significantly enhanced, and their inherent innovative potential will be released. This stimulated internal driving force is the key for human capital to leap from "executors" to "creators".

2.2. Impact of human capital on enterprises' innovation performance

Empowered by the science and technology service industry, the quality and effectiveness of human capital are comprehensively improved, which then directly drives the improvement of innovation performance of intelligent manufacturing enterprises through three key paths.

2.2.1. Learning and absorptive capacity as the foundation of technological innovation performance

In the field of intelligent manufacturing with rapid technological iteration, the ability to acquire, digest, and apply advanced external technologies is crucial. The innovative learning and absorption capabilities of human capital plays a core role here. When enterprise employees have stronger learning capabilities through science and technology services, they can identify valuable external technical information more keenly, understand complex technical principles more quickly, and combine them with the enterprise's existing technical foundation and

production needs.

2.2.2. Collaborative integration capability as the driver of organizational process innovation

Intelligent manufacturing is not only the intellectualization of technology but also a profound transformation of organizations and processes. The enhanced innovative collaboration and integration capabilities of human capital are the soft cornerstone for promoting this transformation. Teams with cross-departmental and cross-organizational collaboration capabilities can more effectively break the departmental walls between R&D, production, sales, and services, and promote end-to-end process reengineering based on customer needs. With the experience of collaborating with external experts through science and technology service platforms, internal enterprise teams can more easily establish efficient internal collaboration mechanisms. This strong knowledge integration and process optimization capability enables enterprises to respond to market changes more agilely, realize small-batch and multi-variety personalized customized production, significantly reduce inventory costs, shorten delivery cycles, and thus significantly improve organizational process innovation performance such as operational efficiency, resource utilization, and customer satisfaction.

2.2.3. Original innovation capability as the source of systemic innovation breakthroughs

Disruptive innovation and fundamental changes in business models often stem from original ideas and the courage to break through conventions. Human capital with original innovation capabilities, stimulated by the innovative environment, is the source of enterprises' systematic innovation breakthroughs. Such teams are not satisfied with incremental improvements but dare to fundamentally question the existing product architecture, production models, and even value propositions, and conduct high-risk and high-return exploration. This business model innovation originates from the core team's systematic thinking beyond the technical level and the courage to create new value. The original innovation capabilities of human capital directly drive enterprises' innovation in management systems, value creation logic, and other in-depth aspects, thereby obtaining long-term and difficult-to-imitate competitive advantages.

2.3. Mediating role of human capital

Human capital plays an indispensable mediating role in the relationship between "science and technology service industry: innovation performance of intelligent manufacturing enterprises". The various service contents, models, and levels of the science and technology service industry do not directly affect enterprises' patent output or production efficiency, but are first received, digested, and internalized by the enterprise's human capital.

Specifically, the service contents of the science and technology service industry, including technical training and knowledge consulting, mainly affect enterprises' performance in product technological innovation and process optimization by improving the innovative learning and absorption capabilities of human capital. The service methods of the science and technology service industry, including collaboration platforms and industry-university-research networks, mainly promote the improvement of enterprises' performance in production process reorganization and organizational agility by enhancing the innovative collaboration and integration capabilities of human capital. The service level of the science and technology service industry, including the innovation atmosphere and the strategic and management consulting provided, mainly drives enterprises to achieve breakthroughs in business model transformation and strategic management system innovation by stimulating the original innovation capabilities of human capital.

This is a gradual transmission and deepening process. Without high-quality human capital as an intermediary, the supply of science and technology services may remain at the transactional level and cannot be transformed into the enterprise's internal innovative momentum. Conversely, even if an enterprise has human resources with great potential, without the continuous nourishment and activation of external science and technology services, it may gradually lose its innovative vitality due to knowledge depletion or rigid thinking. Therefore, human capital is a dynamic and active core transformation hub in this interaction.

3. Countermeasures and suggestions

To promote the positive interaction between the science and technology service industry, human capital, and the innovation performance of intelligent manufacturing enterprises, the government, science and technology service institutions, and enterprises need to work together to build an efficient and open innovation ecosystem.

3.1. Government optimizes the environment, strengthens guidance and basic supply

The government should assume the roles of top-level designer, rule-maker, and public service provider, thereby establishing the institutional and infrastructural foundations necessary for effective interaction among the three parties.

It is essential to improve the policy support system and guide the precise allocation of innovation resources. The government should clearly define development objectives, priority areas, and implementation pathways for intelligent manufacturing and science and technology services. In terms of fiscal policy, a "Special Fund for Intelligent Manufacturing Science and Technology Services" with a stable growth mechanism should be established. Through post-subsidy schemes and government procurement of services, enterprises can receive direct subsidies for purchasing key technical services, effectively reducing innovation costs and risk burdens. In terms of tax policy, preferential corporate income tax policies should be provided to enterprises delivering science and technology services related to intelligent manufacturing. At the same time, manufacturing enterprises investing in digital transformation should be granted incentives such as additional tax deductions to encourage sustained technological upgrading.

Regarding talent policy, high-end professionals in the science and technology service sector should be incorporated into local high-level talent recognition systems. Supporting measures, such as housing subsidies and children's education benefits, should be implemented to address practical barriers to talent attraction and retention, thereby strengthening the human capital base of the industry. The government should build high-level public service platforms to lower the threshold for collaborative innovation. By addressing market failures, it should prioritize investment in infrastructure with public-good attributes and promote an integrated online-offline service model characterized by openness and collaboration. Particular attention should be given to reducing access costs for SMEs. Through mechanisms such as government procurement of services and the issuance of platform usage vouchers, inclusiveness and equitable access to innovation resources can be effectively ensured.

3.2. Science and technology service industry provides precise empowerment and enhances professionalism and collaboration

The science and technology service industry should shift from the traditional role of a "transactional intermediary" to that of an "innovation partner" and "empowerment enabler," embedding itself more deeply into the innovation processes of manufacturing enterprises.

It is necessary to promote the innovation and upgrading of service models by providing integrated and full-cycle solutions. The industry should move beyond fragmented and isolated service provision and instead develop full-chain service models characterized by "consulting + implementation + operation," as well as integrated solution packages combining "hardware + software + content." Such models can better meet the full life-cycle and full value-chain needs of intelligent manufacturing enterprises. At the same time, service providers should actively embrace digital transformation and leverage industrial Internet platforms to cultivate new service formats, including remote intelligent diagnostics, predictive maintenance, energy consumption optimization, and virtual simulation-based training. These digitally enabled services not only enhance efficiency and responsiveness but also create continuous value for client enterprises.

In addition, the industry should deepen industry-university-research-application collaboration and integrate into the core chain of industrial innovation. Science and technology service institutions should proactively extend their presence into industrial parks and key enterprises to accurately identify technological bottlenecks and innovation demands. On this basis, they should establish stable and close cooperative entities with high-level research institutions under mechanisms of "risk sharing and benefit sharing," thereby strengthening long-term strategic collaboration.

Moreover, service institutions should actively participate in, or even take the lead in establishing, industrial technology innovation strategic alliances within specialized sub-sectors. Through organizing joint research on generic and common technologies under alliance frameworks, they can accelerate the engineering application and commercialization of laboratory research outcomes. It is essential to cultivate and attract professional "technology brokers" who possess interdisciplinary expertise, understanding both technology and industry, as well as both R&D and market dynamics. Such hybrid talent plays a pivotal role in bridging the gap between scientific research and industrial application, thereby significantly improving the efficiency and success rate of technology transfer.

3.3. Intelligent manufacturing enterprises take the initiative to integrate and strengthen absorption and re-innovation

Enterprises must update their development philosophies, proactively embrace openness, and effectively leverage external innovation resources to strengthen their core competencies.

Enterprises should establish a strategic mindset grounded in open innovation and systematically integrate science and technology services into core capability development. Senior management must recognize that in an era characterized by networked and open innovation, the capacity to identify, acquire, and integrate global innovation resources has itself become a critical source of competitive advantage. Accordingly, the utilization of science and technology services should be incorporated into the firm's overall innovation strategy, supported by dedicated budgets and clearly assigned organizational responsibilities. Rather than being viewed as short-term technical outsourcing, science and technology services should be regarded as long-term investments in human capital accumulation and the cultivation of dynamic capabilities.

Additionally, enterprises should build dynamic knowledge management mechanisms to ensure the internalization and value-added transformation of external knowledge. Specialized systems and standardized processes should be established to facilitate the codification, sharing, and re-creation of knowledge, skills, and experience acquired through external collaborations and services. For instance, firms may introduce an "external learning report" system requiring employees who participate in external training or collaborative projects to conduct internal knowledge-sharing sessions. Cross-departmental technical task forces can be formed to apply

newly introduced technologies to concrete operational challenges. Regular internal innovation workshops may also be organized to integrate external knowledge with existing expertise and stimulate creative recombination.

Furthermore, the effectiveness of knowledge absorption and internal diffusion should be incorporated into departmental and individual performance evaluation systems. By embedding knowledge management into organizational incentives, enterprises can foster a culture of continuous learning, collective problem-solving, and sustained innovation..

4. Conclusion

This study focuses on the core issue of the mechanism through which the science and technology service industry affects the innovation performance of intelligent manufacturing enterprises via human capital, constructs an integrated theoretical model, and designs a corresponding empirical testing plan. The research not only helps to clarify the logical chain between "external services-internal capabilities-innovation output" and enrich theoretical research in the fields of innovation management and service economy but also, more importantly, its conclusions will provide targeted decision-making references and practical guidelines for promoting the in-depth integration of the science and technology service industry and advanced manufacturing industry and enhancing the innovation capabilities of intelligent manufacturing. Future research can further explore the differentiated impact paths of enterprises with different ownership types and scales, as well as the evolutionary impact of new formats and models of the science and technology service industry on the above mechanisms in the context of digitalization.

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