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Mediating Role of Dynamic Capabilities in Relationship of Industry 4.0 with Innovation Performance of Manufacturing Firms

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Abstract

This study examines the mediating role of dynamic capabilities in adopting Industry 4.0 technologies and its impact on manufacturers' operational and innovation performance, adopting the micro foundational theoretical perspective of dynamic capabilities. Using survey data across multiple countries ranked in the top quartile of the Global Manufacturing Risk Index, the proposed model was empirically tested through multivariate analysis methods. The findings reveal that I4.0 adoption enhances innovation performance for manufacturers in developed countries and improved operational performance for those in developing countries. It is found that dynamic capabilities serve as a key mediator in both cases. However, I4.0 adoption does not significantly impact innovation performance in developing countries or operational performance in developed countries. The study concludes that manufacturers can maximize the benefits of I4.0 investments through a strategic focus on leveraging dynamic capabilities. The outcomes vary by economic context, enabling operational excellence in developing countries and driving innovation leadership in developed countries.

Keywords
Dynamic capabilities, Industry 4.0, Innovation performance, Operational excellence, Lean.

1. Introduction
In today's highly competitive manufacturing landscape, Industry 4.0 (I4.0) has revolutionized production systems by integrating cyber-physical systems (CPS), Internet of Things (IoT), artificial intelligence (AI), and big data analytics. This shift has transformed manufacturing from a machine-centric model to a digitally interconnected ecosystem, enabling firms to achieve greater agility, efficiency, and innovation (Kumar et al., 2018; Zhang et al., 2020; Olsen & Tomlin, 2020). Prominent industry leaders have embraced I4.0 technologies to drive operational excellence. For instance, Siemens' digital factory leverages robotics and real-time analytics to ensure comprehensive data integration across development, production, and supplier networks. Similarly, Bosch Automotive's Wuxi, China plant uses IoT and big data-driven systems to detect bottlenecks in diesel system manufacturing, optimizing production processes. Another example is Fast Radius' Chicago facility, recognized by the World Economic Forum as a top-tier smart factory, which has pioneered additive manufacturing capabilities. These cases underscore how I4.0 enables firms to enhance their manufacturing intelligence, process automation, and decision-making capabilities.

However, the adoption of I4.0 requires significant investment, prompting firms to evaluate its tangible benefits before implementation. One critical aspect that practitioners and policymakers must assess is whether I4.0 adoption translates into improved operational and innovation performance. While firms adopting I4.0 technologies often report enhanced efficiency and productivity, the impact on innovation performance remains ambiguous, particularly in different economic and technological contexts. Some studies indicate that developed economies benefit from increased R&D

output, patent filings, and breakthrough innovations, while developing economies experience greater efficiency gains but limited innovation advancements. This study seeks to address these discrepancies by investigating the mechanisms through which I4.0 adoption influences both operational and innovation performance across different national contexts.

To understand this dynamic relationship, the study adopts the dynamic capabilities (DC) view, a theoretical framework that explains how firms sense, seize, and reconfigure their capabilities in response to evolving competitive environments (Teece et al., 1997). The DC perspective is particularly relevant to I4.0 adoption, as prior research suggests that digital transformation fosters an organization's ability to adapt to rapidly changing technological landscapes. The ability to integrate, build, and reconfigure internal and external competencies is crucial for firms leveraging I4.0 technologies. For example, the deployment of predictive maintenance systems, AI-driven quality control, and real-time supply chain optimization exemplifies how firms dynamically adjust their operations to maintain competitiveness.

Unlike previous industrial revolutions that primarily introduced mechanization (Industry 1.0), mass production (Industry 2.0), and automation (Industry 3.0), Industry 4.0 integrates digital technologies, advanced materials, and intelligent systems to create smart, adaptive manufacturing. This study investigates how digital capabilities mediate the relationship between I4.0 adoption and innovation performance, emphasizing the role of technological infrastructure, workforce skills, and organizational agility in maximizing I4.0 investments. By leveraging empirical data from manufacturing firms across top-ranked nations in the Global Manufacturing Risk Index, this research aims to provide evidence-based insights on the strategic value of I4.0 adoption. Ultimately, the study highlights the need for firms to develop dynamic capabilities to unlock the full potential of I4.0, ensuring sustainable competitive advantage in both developed and developing economies.

1.1 Objectives

Specifically, the research addresses two key questions:

1. How does I4.0 adoption influence the operational and innovation performance of manufacturing firms?
2. How do digital capabilities mediate this association?

2. Literature Review

The literature provides extensive evidence on the adoption of Industry 4.0 (I4.0) in manufacturing and its associated benefits. For instance, Cagliano et al. (2019) demonstrated how smart manufacturing enabled by I4.0 adoption impacts work organization at both micro and macro levels. Similarly, Bag et al. (2021) highlighted how I4.0 delivery systems help firms develop circular economy-based manufacturing competencies. Additionally, studies by Porter and Heppelmann (2014) and Wang et al. 2016 emphasized how I4.0 facilitates flexible manufacturing and functions as a decision-support system by processing large volumes of data. These studies underscore the operational benefits of I4.0, such as increased productivity, reduced cycle times, and improved resource utilization efficiency.

Furthermore, practitioners have expressed significant interest in I4.0 applications within the manufacturing sector. According to the Boston Consulting Group, the pace of I4.0 adoption is expected to accelerate over the next decade Rubmann et al. (2015), underscoring its growing practical significance for the industry.

Frank et al. (2019) highlighted that I4.0 adoption resulted in poorer innovation outcomes compared to non-I4.0 innovation activities. Similarly, Dalenogare et al. (2018) observed, somewhat unexpectedly, that I4.0 technologies such as big data exhibited a negative association with product performance, contrary to their intended role in driving innovation. These contrasting findings underscore the need for an empirical investigation into the impact of I4.0 on innovation performance to address these ongoing debates.

In addition to being a valuable resource, Industry 4.0 (I4.0) serves as a connector, integrating organizational resources and enabling smart operational functioning. As such, it functions as a resource for adapting to change, aligning seamlessly with the framework of dynamic capabilities (DCs) (Teece et al., 1997) Furthermore, I4.0 offers significant utility in monitoring and controlling machines, products, and services. It facilitates real-time data collection, analysis, and transmission of large data volumes, processed through cybernetic models, which form the foundation for effective operational decision-making (Benitez et al., 2020).

3. Methods

This study employed a survey research design to systematically examine the relationship between Industry 4.0 (I4.0) adoption, dynamic capabilities, and firm performance. The unit of analysis comprised manufacturing firms that have implemented I4.0 technologies to a significant extent. A structured questionnaire was developed, incorporating validated measurement scales to ensure reliability and construct validity. Data collection targeted firms across multiple countries ranked in the top quartile of the Global Manufacturing Risk Index. The proposed model was empirically tested using structural equation modeling (SEM), allowing for the assessment of causal relationships and mediation effects while controlling for firm-specific and contextual variations.

4. Data Collection

To investigate these relationships, we analyzed survey data from manufacturing firms across multiple countries, encompassing three developing and three developed nations ranked in the top quartile of the Global Manufacturing Risk Index**.** This study provides empirical insights into the role of digital capabilities in maximizing the benefits of I4.0 adoption across diverse economic contexts.

5. Results and Discussion

The structural equation modeling (SEM) results revealed the following findings regarding the direct effects in the structural model:

- H1: The hypothesis was supported in the developing country sample ($\beta = 0.1$, $t = 2.4$, $p < 0.01$), but it was not supported in the developed country sample ($\beta = 0.01$, $t = 0.427$, not significant).
- H2: Support was found for the developed country sample ($\beta = 0.39$, $t = 3.73$, $p < 0.001$), but no support was observed in the developing country sample ($\beta = 0.15$, $t = 1.2$, not significant).
- H3: The relationship between innovation performance and operational performance was supported in the developed country sample ($\beta = 0.6$, $t = 2.7$, $p < 0.01$), but it was not supported in the developing country sample ($\beta = -0.10$, $t = 0.6$, not significant).
- H5: The association between I4.0 technologies and dynamic capabilities (DC) was supported in both the developed country sample ($\beta = 0.5$, $t = 5.5$, $p < 0.00$) and the developing country sample ($\beta = 0.66$, $t = 6.275$, $p < 0.001$). These results indicate nuanced differences in how Industry 4.0 technologies and their associated factors influence performance outcomes across developed and developing countries. The results are summarized in Table 1.

Table 1. Results of Hypothesis Tests

Hypothesis	Developing Country (β, t-value, p-value)	Developed Country (β, t-value, p-value)
H1	$\beta = 0.1$, $t = 2.4$, $p < 0.01$ (Supported)	$\beta = 0.01$, $t = 0.427$, Not Significant
H2	$\beta = 0.15$, $t = 1.2$, Not Significant	$\beta = 0.39$, $t = 3.73$, $p < 0.001$ (Supported)
H3	$\beta = -0.10$, $t = 0.6$, Not Significant	$\beta = 0.6$, $t = 2.7$, $p < 0.01$ (Supported)
H5	$\beta = 0.66$, $t = 6.275$, $p < 0.001$ (Supported)	$\beta = 0.5$, $t = 5.5$, $p < 0.00$ (Supported)

The mediation analysis results revealed distinct patterns for mutiple country samples:

- For the industry 4.0 and operational performance relationship mediated by innovation performance:
  - In the developed country sample, there was evidence of full mediation (total effect = 0.6, indirect effect = 0.2, $p < 0.01$).
  - In the developing country sample, no mediation effect was observed (total effect = 0.7, indirect effect = 0.0, not significant).
- For H6, which examined the mediating effect of dynamic capabilities on the industry 4.0 and innovation performance relationship:
  - In the developed country sample, partial mediation was supported (total effect = 0.6, indirect effect = 0.19, $p < 0.01$).
  - In the developing country sample, full mediation was observed (total effect = 0.646, indirect effect = 0.356, $p < 0.05$).

- For H7, investigating the mediating effect of dynamic capabilities on the industry 4.0 and innovation performance relationship
- Partial mediation was found in the developed country sample (total effect = 0.8, indirect effect = 0.3, $p < 0.01$).
- Similarly, partial mediation was observed in the developing country sample (total effect = 0.675, indirect effect = 0.528, $p < 0.01$). Results of mediation tests are summarized in Table 2.

Table 2. Results of Mediation tests

Hypothesis	Developing Country (Total Effect, Indirect Effect, p-value)	Developed Country (Total Effect, Indirect Effect, p-value)	Mediation Type
Industry 4.0 → Operational Performance (Mediated by Innovation Performance)	Total Effect = 0.7, Indirect Effect = 0.0, Not Significant	Total Effect = 0.6, Indirect Effect = 0.2, p < 0.01	No Mediation (Developing), Full Mediation (Developed)
H6: Industry 4.0 → Innovation Performance (Mediated by Dynamic Capabilities)	Total Effect = 0.646, Indirect Effect = 0.356, p < 0.05	Total Effect = 0.6, Indirect Effect = 0.19, p < 0.01	Full Mediation (Developing), Partial Mediation (Developed)
H7: Industry 4.0 → Innovation Performance (Mediated by Dynamic Capabilities)	Total Effect = 0.675, Indirect Effect = 0.528, p < 0.01	Total Effect = 0.8, Indirect Effect = 0.3, p < 0.01	Partial Mediation in Both

These findings highlight the varying roles of innovation performance and dynamic capabilities as mediators in developed and developing economies, reflecting the contextual differences in how Industry 4.0 technologies influence operational and innovation outcomes.

6. Conclusion

Building on dynamic capabilities (DC) theory, this study examines the role of DC in Industry 4.0 (I4.0) adoption across separate samples from developed and developing countries. The findings, derived from direct and mediation effect analyses, highlight the critical role of DC in enhancing both operational and innovation performance. Furthermore, the results validate the core concepts and assumptions of DC microfoundations in manufacturing contexts, emphasizing their importance in fostering the development of smart factories.

The results of mediation analysis highlight the pivotal role of dynamic capability (DC) formation in achieving performance outcomes across both developed and developing economies. For instance, in a developing economy, a manufacturing firm focused on building DCs might prioritize initiatives such as employee training programs to enhance skills in data analysis and technology utilization, thereby equipping the workforce to effectively adapt to the changes brought by Industry 4.0**.**

References

Bag, S. Gupta, and S. Kumar, “Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development,” Int. J. Prod. Econ., vol. 231, 2021, Art. no. 107844, doi: 10.1016/j.ijpe.2020.107844.

Benitez, X. Luo, and G. Vastag, “Information and Operational Decision Sciences: The interplay of Information technology and operational decision sciences,” Decis. Sci., vol. 51, no. 3, pp. 458–463, 2020, doi: 10.1111/deci.12422

Cagliano, R , F. Canterino, A. Longoni, and E. Bartezzaghi, “The interplay between smart manufacturing technologies and work organization,” Int. J. Oper. Prod. Manage., vol. 39, no. 6/7/8, pp. 913–934, 2019, doi: 10.1108/IJOPM-01-2019-0093.

Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, “The expected contribution of Industry 4.0 technologies for industrial performance,” Int. J. Prod. Econ., vol. 204, pp. 383–394, 2018, doi: 10.1016/j.ijpe.2018.08.019.

Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," Int. J. Prod. Econ., vol. 210, pp. 15–26, 2019, doi: 10.1016/j.ijpe.2019.01.004.

Kumar, S. V. Mookerjee, and A. Shubham, "Research in operations management and information systems interface," Prod. Oper. Manage., vol. 27, no. 11, pp. 1893–1905, 2018, doi: 10.1111/poms.12961

Olsen T. L. and B. Tomlin, "Industry 4.0: Opportunities and challenges for operations management," Manuf. Serv. Oper. Manage., vol. 22, no. 1, pp. 113–122, 2020, doi: 10.1287/msom.2019.0796.

Porter M. E. and J. E. Heppelmann, "How smart, connected products are transforming competition," Harvard Bus. Rev., vol. 92, no. 11, pp. 64–88, 2014.

Rubmann et al., "Industry 4.0: The future of productivity and growth in manufacturing industries," Boston Consulting Group, 2015.

Teece, D. J. , G. Pisano, and A. Shuen, "Dynamic capabilities and strategic management," Strategic Manage. J., vol. 18, pp. 509–533, 1997, doi: 10.1002/(SICI)1097-0266(199708)18:73.0. CO;2-Z.

Wang, A. Gunasekaran, E. W. T. Ngai, and T. Papadopoulos, "Big data analytics in logistics and supply chain management: Certain investigations for research and applications," Int. J. Prod. Econ., vol. 176, pp. 98–110, Jun. 2016, doi: 10.1016/j.ijpe.2016.03.014.

Zhang, X. Wu, C. S. Tang, T. Feng, and Y. Dai, "Evolution of operations management research: From managing flows to building capabilities," Prod. Oper. Manage., vol. 29, no. 10, pp. 2219–2229, 2020, doi: 10.1111/poms.13231

Biography

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