The Future of BPM in the Era of Industry 4.0: Exploring New Opportunities for Innovation

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Abstract: In today's digital age, the fourth industrial revolution has given rise to Industry 4.0. This new paradigm has brought new challenges for organizations, through a digital transformation. This digital transformation has profoundly impacted the way businesses operate, leading to a fundamental shift in the Business Process Management (BPM), affecting business models, processes, products, relationships and competencies. This transformation is based on the use of cyber-physical systems and information and communication technologies, in particular artificial intelligence and the Internet of Things. This paper aims to identify and define the main challenges, limitations, and opportunities of BPM in the era of Industry 4.0. Furthermore, it aims to identify potential future research directions. in addition to analyzing the impact of Industry 4.0 concepts and related technologies on the management of organizations and their business processes.

1 INTRODUCTION

The advent of contemporary technological advances has led to the emergence of Industry 4.0, which can be regarded as a consequence of the Fourth Industrial Revolution (Xu, Xu, et Li 2018). This new paradigm has brought changes in the functioning of the organization through a digital transformation affecting business models, processes, products and skills (Flechsig et al. 2022). In the current business environment, characterized by intense competition, a fail-fast culture is imperative for organizations to succeed (Szelągowski et Berniak-Woźny 2022). Organizations are integrating digital technologies into their core business processes to enhance efficiency, improve customer experience, and drive innovation (Vaska et al. 2021). In the era of Industry 4.0, organizations are confronted with complex implementation issues surrounding the digital transformation. These issues include the adoption of new Cyber-Physical Systems (CPS) and smart factory technologies as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics, as well as the adaptation or replacement of core Enterprise Architectures (EA), Communication Technologies (ICT) infrastructures and processes (Xu, Xu, et Li 2018).

Unfortunately, many organizations lack the necessary capabilities to effectively address these issues (Di Ciccio, Marrella, et Russo 2015; Szelągowski et Berniak-Woźny 2022). Consequently, these organizations are carrying out such transformation to adapt to the emerging paradigm. This shift has led to the need for efficient and effective BPM.

The transition from traditional industrial ecosystems to Industry 4.0 will require not only the development of new Information and ICT but also the creation of new business models; The advent of digitalization has profoundly impacted the way businesses operate, leading to a fundamental shift in the management of business processes (Colombo, Schleuter, et Kircher 2015; Arnold, Kiel, et Voigt 2016). In this context, business process management (BPM) plays a crucial role in supporting organizations to achieve greater flexibility and responsiveness (Grisold et al. 2021). It presents a valuable and an advantageous tool through cost reduction, process excellence, and continuous process improvement, enabling organizations to design, analyze, execute, monitor and optimize important processes (Gartner 2018).

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According to Gartner in (Gartner 2018), BPM is critical for the success of business transformation initiatives. BPM can deliver this level of agility to business operations in combination with other disciplines, such as EA (Gartner 2016).

Furthermore, BPM plays a crucial role in helping organizations identify and optimize their key business processes. It enables organizations to quickly adapt to changing business environments, including humans, applications, and technology (Liu, Chen, et Chou 2011). Ultimately, this leads to improved operational efficiency and increased competitiveness (Gartner 2018; Viriyasitavat et al. 2019; Baiyere, Salmela, et Tapanainen 2020; Butt 2020; Szelągowski et Berniak-Woźny 2022).

In alignment with the aforementioned concepts, this paper discusses the BPM limitations, opportunities, and challenges in the era of Industry 4.0 and provides insights into how organizations can leverage BPM to improve their operational efficiency, customer experience, innovation, and competitiveness. Additionally, the paper aims to identify potential future research directions and analyze the impact of Industry 4.0 concepts and related technologies on the management of organizations and their business processes.

The remainder of this paper is organized as follows: Section 2 provides a theoretical overview of the fundamental concepts related to this study, basing on an analysis of existing literature. Section 3 presents the challenges associated with Industry 4.0. Section 4 offers a comprehensive overview of BPM. Section 5 presents a systematic literature review (SLR) on BPM in the era of Industry 4.0. Section 6 explores the opportunities that Industry 4.0 presents for BPM. Finally, Section 7 concludes with an analysis of the findings, and outlines potential future research directions.

2 THEORETICAL BACKGROUND

The fourth industrial revolution, commonly referred to as Industry 4.0, represents a significant shift in the way industries operate, driven by the convergence of digitalization, digital transformation, and emerging technologies (Gajšek and Vujica Herzog 2020). This section aims to introduce these foundational concepts, providing a comprehensive understanding of their interrelationships and implications for modern industry.

2.1 Digitalization

Digitization is the process of encoding analog information into digital formats enabling computers to store processes, and transmit such information effectively. In contrast, digitalization describes how to use digital technology to change existing business processes" (Lee et al. 2021). According to Berlak et al. in (Berlak, Hafner, et Kuppelwieser 2021), digitalization involves optimizing existing business processes through enhanced integration and coordinated collaboration, in order to facilitate the creation of new business opportunities.

2.2 Digital Transformation

Digital Transformation is the further stage after digitalization, describing the successful upgrade and change that leads to a new business model (Lee et al. 2021). It can be defined as the process of integrating digital technologies and business processes within a digital economy. This transformation focuses on the restructuring business operations to fully facilitating the use of a company's core competencies through digital technology to achieve a competitive advantage (Liu, Chen, et Chou 2011). In the context of BPM, digital transformation refers to the transformation of business operations, services and models. This comprehensive transformation covers all processes within the enterprise, ultimately to building a digital model of the enterprise, incorporating digitized process attributes (Tupa et Steiner 2019).

2.3 Industry 4.0

The term "Industry 4.0" was first introduced in 2011 at the Hannover Fair in Germany (Adolph et al. 2016). This concept, often referred to as the Fourth Industrial Revolution, has emerged in the manufacturing industry (Xu, Xu, et Li 2018). Implementing Industry 4.0 involves a number of different technologies and techniques, including CPS, IoT, cloud computing, blockchain, industrial information integration and other related technologies (Xu, Xu, et Li 2018). Industry 4.0 is often described as the Era of Intelligence, which integrates information technology and operational technology to achieve intelligence in a mass customization paradigm, introducing technologies such as the Internet of IoT, big data, AI, CPS, and robotics into the factory environment (Guo et al. 2024).

3 INDUSTRY 4.0 CHALLENGES

The rapid evolution of Industry 4.0 technologies has transformed the landscape of modern industry, creating exceptional opportunities for innovation and efficiency. However, organizations often face a variety of challenges that can hinder the successful implementation and integration of these advanced technologies (Gažová, Papulová, et Smolka 2022). Key challenges include usability (Zhang et al., 2020), computational efficiency (Yang, Q. et al. 2019), scalability (Bai et al., 2020), interoperability, and storage capacity (Su et al. 2023). The implementation of advanced technologies also introduces potential risks that organizations must carefully manage, including cyber security threats, data privacy concerns, and the possibility of significant disruptions during the transition phase (Almubarak et al., 2020). The Industry 4.0 approach relies on the deployment of intelligent, interconnected Cyber-Physical Systems (CPS), which presents significant security challenges. Many of these systems were not originally designed with cyber security considerations, making cyber security a critical concern for organizations adopting the Industry 4.0 paradigm (Corallo, Lazoi, et Lezzi 2020). Another significant challenge of Industry 4.0 is its insufficient focus on human-centricity and system resilience.(Guo et al. 2024). Additionally, the integration of AI, IoT, and Blockchain within BPM introduces several challenges, including developing business process collaboration, managing large data volumes, implementing smart contracts, ensuring interoperability with Blockchain technology, achieving standardization, and addressing security and privacy concerns. (Viriyasitavat et al. 2018). Currently, the management of Business processes in industry 4.0 faces significant challenges, including centralization, lack of verifiability, trust issues, and insufficient automation (Stefanescu, D. et al., 2024). This context highlights the importance of smart contracts, which can address these shortcomings by providing a more decentralized and automated approach to BPM.

4 BUSINESS PROCESS MANAGEMENT

Business Process Management (BPM) is the combination of knowledge from business administration and information technology, applied to operational business processes (Weske 2019). In practice, BPM is the application of methods, techniques, and software to design, enact, control, and analyze operational processes that involve humans, organizations, applications, documents, and other sources of information (van der Aalst, ter Hofstede, et Weske 2003; Di Ciccio, Marrella, et Russo 2015). The emergence of Industry 4.0 has brought new challenges for organizations requiring them to address the complexities of implementing the latest Industry 4.0 technologies (Colombo, Schleuter, et Kircher 2015; Arnold, Kiel, et Voigt 2016). In the current digital era, it is imperative that established BPM tools are adapted in order to align with the evolving needs of enterprises (Viriyasitavat et al., 2019). This involves not only the integration of novel technologies but also the creation of new business models and the adaptation or even replacement of existing core EA, ICT infrastructures and business processes (Xu, Xu, et Li 2018).

5 BPM IN THE AGE OF INDUSTRY 4.0: A SYSTEMATIC LITERATURE REVIEW

Many studies emphasize the critical role of BPM in driving digital transformation and enhancing operational efficiency in industry 4.0. While BPM presents opportunities for industry 4.0, it also faces significant limitations and challenges in this new era. This section outlines a study focused on identifying these challenges and exploring potential solutions. A systematic literature review (SLR) of academic research on Industry 4.0 and BPM was conducted to analyze existing limitations and challenges, as well as to identify potential opportunities for overcoming them.

5.1 Methodology

This research employs a systematic literature review approach, aligned with PRISIMA guidelines (Moher et al. 2010), and comprises seven phases:

Phase 1: involved searching for articles in the Science direct, IEEE, and ACM**.** using keywords, ("business process management" OR "BPM") AND ("challenges" OR "limitations" OR "opportunities") AND (“Industry 4.0”) to focus on BPM related challenges, limitations and opportunities.

Phase 2: excluded publications prior to 2015, ensuring the inclusion of literature, by targeting articles published between 2015 and 2025.

Phase 3: selected articles by subject area, including manufacturing, Business, Management and Accounting, Engineering, Computer Sciences, Decision Sciences.

Phase 4: excluded no English publications.
Phase 5: exclusion of papers according to article type, research and review papers only.
Phase 6: retained journals ranked in the top two quartiles (Q1 and Q2) of the SCImago database
Phase 7: involves evaluation of the titles and abstracts based on the paper's coverage of the opportunities, challenges or limitations of BPM and/or proposals for future BPM improvements.

This analysis resulted in 22 selected papers summarized in Table 1 and selected papers are detailed in Table 2.

Table 1: Number of works published in the Science direct, IEEE and ACM in the period 2015-2025.

Phases / Database	Science Direct/ Elsevier	IEEE	ACM
Phase 01	4268	2848	3571
phase 02	2571	1212	1389
Phase 03	2130	1121	988
Phase 04	2127	1118	988
Phase 05	1853	129	122
Phase 06	1168	76	88
Phase 07	13	6	3

Table 2: Selected paper according to the paper's coverage.

Database	Science direct	Science direct	Science direct	Science direct	Science direct	Science direct	Science direct	Science direct	Science direct
Authors	(Su et al. 2023)	(Guo et al. 2024)	(Van Looy 2021)	(Bai, C. et al. ,2020)	(Kamble, S. S., Gunasekaran, A., Ghadge, A., & Raut, R. 2020)	(Soufi et al. 2022)	(Saraeian, Shirazi, et Motameni 2018)	(Czvetkó et al. 2022)	Schulte et al. 2015)
Title	Technical challenges of Blockchain technology for sustainable manufacturing paradigm in Industry 4.0 era using a fuzzy decision support system	Industrial metaverse towards Industry 5.0: Connotation, architecture, enablers, and challenges	a quantitative and qualitative study of the link between business process management and digital innovation	Industry 4.0 technologies assessment: A sustainability perspective	performance measurement system for industry 4.0 enabled smart manufacturing system in SMMEs-A review and empirical investigation	Uncertainty of key performance indicators for Industry 4.0: A methodology based on the theory of belief functions	Towards an extended BPMS prototype: Open challenges of BPM to flexible and robust orchestrate of uncertain processes	Data-driven business process management-based development of Industry 4.0 solutions	Elastic Business Process Management: State of the art and open challenges for BPM in the cloud
Journal Title	Technological Forecasting & Social Change	Journal of Manufacturing Systems	Information & Management	International Journal of Production Economics	. International journal of production economics	Computers in Industry	Computer Standards & Interfaces	CIRP Journal of Manufacturing Science and Technology	Future Generation Computer Systems
Journal quality assessment score	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1
Citation	58	6	77	847	705	14	19	24	96

Database	Science direct	IEEE	Science direct	Science direct	IEEE	Science direct	Science direct	IEEE	Elsevier	IEEE
Authors	(Pourmirza et al. 2017)	(Elghaish et al. 2021)	(Viriyasitavat et al. 2019)	(Arnold, Kiel, et Voigt 2016)	(Baiyere, Salmela, et Tapanainen 2020)	(S. Moreira, et al, 2024)	(Garcia-Garcia, etal .,2020)			
Title	A systematic literature review on the architecture of business process management systems	Blockchain and the ‘ Internet of Things’ for the construction industry: research trends and opportunities	Blockchain and Internet of Things for Modern Business Process in Digital Economy	How Industry 4.0 changes business models in different manufacturing industries	Digital Transformation and the New Logics of Business Process Management	Business Process Automation in SMEs: A Systematic Literature Review	Using Blockchain to Improve Collaborative Business Process Management: Systematic Literature Review			
Journal Title	Information Systems journal	Automation in Construction	IEEE Transactions on Computational Social	International Journal of Innovation Management	European Journal of Information Systems	IEEE Access	In Advances In Computers			
Journal quality assessment score	Q1	Q1	Q1	Q2	Q1	Q1	Not assigned yet			
Citation	44	127	118	252	551	3	67			

Database	IEEE	IEEE	ACM	ACM
Authors	(Bartlett, L., et al.,2023).	(Ahmed S. and Shahzad K., 2022).	(Cardoso P. B., et al., 2024)	(Stefănescu, D. et al.,2024)	(Yang, Q. et al. 2019)
Title	A review on business process management system design: the role of virtualization and work design.	Augmenting Business Process Model Elements with End-User Feedback	A Granular Risk Analysis Approach for IoT-Aware Business Processes	Smart Contract Powered Framework for the Next Generation Industry 4.0 Business Model	Federated machine learning: Concept and applications.
Journal Title	IEEE Access	IEEE Access	IEEE Access	Distributed Ledger Technologies: Research	ACM Transactions on Intelligent Systems and
Journal quality assessment score	Q1	Q1	Q1	Note assigned yet	Q1
Citation	5	5	1	1	7079

5.2 Findings

This section analyzes the findings on the opportunities, challenges and limitations of current BPM, along with recommended future directions. The analysis is based on the analysis of 22 selected documents listed in Table 2.

5.2.1 BPM Opportunities for Industry 4.0

In the Industry 4.0 era, improving business processes provides new opportunities for organizational transformation, including the redesign of business models and value chains (Gancarczyk et Ujwary-Gil 2020), it establishes new alliances with IT, reinforcing strategic goals, and improving optimizing the efficiency and flexibility of the enterprise’s daily operations (Xu, Xu, et Li 2018; Gancarczyk et Ujwary-Gil 2020; Saraeian, Shirazi, et Motameni

2018; Castro et Teixeira 2021; Kernytska 2024). In the context of Industry 4.0 and smart manufacturing systems, BPM plays a crucial role in ensuring that processes are efficient, agile, and capable of adapting to new technologies and market demands (Kamble, S. S., Gunasekaran, A., Ghadge, A., & Raut, R. 2020). The implementation of BPM significantly impacts Industry 4.0. Companies adopting advanced BPM strategy report benefits, such as increased production efficiency, improved performance monitoring, cost savings, and a higher rate of automation in production (Gažová, Papulová, et Smolka 2022).

Furthermore, BPM can drive process innovation and digital transformation in organizations (Mendling et al. 2020) by enhancing innovation, agility, and sustainability through the integration of technologies like AI, IoT, and Blockchain (Kernytska 2024). Moreover, BPM enables organizations to adapt to changing environments, enhancing their ability to leverage emerging technologies and respond swiftly to market fluctuations (Ortt, Stolwijk, et Punter 2020). BPM plays a crucial role in enabling organizations to comply with industry standards, mitigate risks, and enhance intellectual capital in the digital era (Broccardo et al. 2024). By automating and streamlining business processes, BPM significantly improves operational efficiency and effectiveness (Nosalska et al. 2019). Furthermore, it enhances customer experience by enabling organizations to deliver more personalized and responsive services (Chauhan et Singh 2019).

In conclusion, BPM is a key tool to support the digital transformation of organizations, enabling them to become more competitive, innovative and agile (Kernytska 2024).

5.2.2 BPM Challenges and Limitations in the Era of Industry 4.0

While BPM has long been recognized as a key driver of organizational efficiency, the digital age presents new challenges (Imgrund and Janiesch 2019). These challenges include the complexity of integrating multiple systems and technologies, concerns about data security and privacy, and the need to upskill the workers. Resistance to up-skilling the workforce and organizational changes can hinder BPM implementation in Industry 4.0 (Szelągowski and Berniak-Woźny 2022). Additionally, organizations must enhance flexibility and adaptability to respond to rapidly changing market conditions and technological advancements (Chauhan and Singh 2019). Integrating BPM with emerging technologies like AI, blockchain, and IoT make process management more complex and subject to uncertainty, posing significant challenges for decision-making (Souifi et al. 2022). Current BPMSs often manage only certain processes leading to diverging expectations and outcomes (Saraeian, Shirazi, and Motameni 2018; Pourmirza et al. 2017). Moreover, the complexities of CPS, which integrate computational and physical capabilities, require effective uncertainty management to ensure reliability (Souifi et al. 2022). The growth of data and technology has led to significant changes in business operations. Finally, the challenge of digital innovation, particularly in creating value from data, requires a transformation in BPM (Van Looy, 2021). Security and openness, along with cost and flexibility, represent a significant challenge in BPM, particularly in BPM system components that include IoT devices. BPM systems must seamlessly interact with these technologies and to be able to leverage their capabilities and improve business processes (Elghaish et al. 2021).

BPM discipline has been subjected to significant challenges in recent years, particularly in the context of dynamic and complex business environments of industry 4.0 (Grisold et al. 2021). Companies must offer higher quality, customized products at competitive prices and greater flexibility to improve connectivity in their business processes (Fatorachian and Kazemi, 2018). To achieve this, organizations need properly coordinate their local and external business units, thereby improving BPM flexibility and optimazing the value chain of inter-organizational business processes (Bazan and Estevez 2022). The effectiveness of BPM systems in Industry 4.0 can be compromised by data quality issues. Ensuring high-quality data is essential for accurate decision-making and optimal performance within these systems (Yokogawa, 2020). The verification of transactions, for instance, has emerged as a significant challenge within the domain of business processes (Viriyasitavat et al. 2019). In their study, Kerpedzhiev et al. in (Kerpedzhiev et al. 2021) introduced a new interpretation of the success factors related to BPM from a digital Innovation perspective. This perspective emphasizes the dynamic interplay between technological advancements and organizational processes, highlighting how digital tools and methodologies can enhance BPM effectiveness. However, additional research is required to develop process innovation theories, models, and applications that are context-specific and applicable to various business environments (Van Looy, 2021).

5.2.3 BPM Future Directions

The challenges identified in BPM also present significant opportunities for experts in business informatics to develop innovative solutions and frameworks. (Kerpedzhiev et al. 2021) outline key challenges that BPM must address over the next decade, emphasizing the importance of strategic alignment between BPM and business objectives to achieve meaningful results. A critical direction for BPM is the integration of AI and machine learning, which can facilitate more intelligent and autonomous business processes (Chauhan & Singh, 2019). Additionally, blockchain technology can enhance transparency, security, and trust in business processes (Ortt, Stolwijk, & Punter, 2020), while IoT will enable real-time monitoring and optimization, improving visibility and information sharing across supply chains (Paksoy, Koçhan, & Ali, 2021). These technologies can provide greater flexibility in production and product design, reducing development time and enabling the production of high-quality, customized products (Chauhan & Singh, 2019; Fatorachian & Kazemi, 2018). Exploring the intersection of IoT data and BPM can lead to adaptive processes that respond in real-time to changing conditions. Furthermore, frameworks that integrate IoT technologies into existing BPM systems are essential for maximizing the benefits of digital transformation while ensuring robust risk management (Cardoso et al., 2024). The scalability and adaptability of BPM systems are crucial for meeting the evolving demands of Industry 4.0 (Rosemann & vom Brocke, 2015). Current BPM systems manage only certain processes, creating opportunities for further research. Addressing challenges related to security, cost, and flexibility through blockchain technology (BCT) can facilitate peer-to-peer transactions, reducing reliance on central authorities (Garcia-Garcia et al., 2020). In this context, BCT has to be integrated with BPM system components that usually include IoT devices (Elghaish F., et al, 2021). BPM should also focus on balancing innovation and efficiency (Sliż, 2024) by exploring digital options for process improvements, complementing its traditional internal focus (Eikebrokk, Olsen, & Garmann-Johnsen, 2024).

6 BPM: CAPITALIZING ON INDUSTRY 4.0 OPPORTUNITIES

The emergence of Industry 4.0 has transformed BPM by enabling process automation, enhancing decision-making capabilities, and increasing agility in responding to market demands. A key opportunity lies in improved process automation through the integration of technologies such as IoT, AI, and machine learning, which drive efficiency, cost reduction, and quality enhancements (Nozari et al., 2024; Bartlett et al., 2023). Digitalization of business processes opens new avenues for innovative business models and organizational structures (Broccardo et al., 2024). The integration of information and communication technology (ICT) with BPM not only streamlines operations but also allows organizations to swiftly adapt to changing market conditions (Moreira et al., 2024). Furthermore, the convergence of BPM with emerging technologies enhances organizational efficiency and drives transformation across various industries by facilitating information transparency, data analysis, and rapid decision-making (Elghaish et al., 2021). Industry 4.0 also emphasizes customer-centric processes, aligning business operations with customer needs to deliver personalized and efficient experiences (Ahmed & Shahzad, 2022). The advancement of IoT technology enables organizations to implement IoT-aware business processes, enhancing their ability to sense and respond proactively to environmental changes (Cardoso et al., 2024). Overall, Industry 4.0 offers substantial cost savings in manufacturing through improved process control, real-time monitoring, and enhanced decision-making (Ghobakhloo, 2020; Fatorachian & Kazemi, 2018).

7 SYNTHESIS AND CONCLUSIONS

This systematic literature review has made several significant contributions to the research domain at the intersection of BPM and Industry 4.0:

- **A Comprehensive Overview**: The SLR provides a thorough examination of the current state of research on BPM in the context of Industry 4.0, highlighting key opportunities, limitations, and future research directions. This comprehensive overview serves as a foundational resource for researchers and practitioners seeking to understand the evolving landscape of BPM in the digital age.
- **Identification of Key Challenges and Opportunities**: By synthesizing existing literature, this review identifies critical challenges that organizations face when integrating BPM with Industry 4.0 technologies,

such as data security, process standardization, and the need for agility. Additionally, it highlights the opportunities presented by advanced technologies like AI, IoT, and blockchain, which can enhance process automation and decision-making.

- **Framework for Future Research**: The findings of this review outline a framework for future research that emphasizes the need for studies focused on the integration of BPM with emerging technologies. This framework encourages researchers to explore innovative practices that balance traditional BPM principles with the demands of Industry 4.0, thereby advancing theoretical and practical knowledge in the field.
- **Insights into Risk Management**: The review underscores the role of BPM in establishing robust risk management processes in the face of increased cybersecurity threats and data privacy concerns. This insight contributes to the literature by emphasizing the importance of integrating risk management into BPM frameworks, particularly in the context of digital transformation.
- **Focus on Customer-Centric Processes**: The synthesis highlights the shift towards customer-centric processes facilitated by Industry 4.0 technologies. This contribution encourages further exploration of how BPM can be adapted to enhance customer experiences and align business processes with customer needs in a rapidly changing environment.
- **Call for Interdisciplinary Research**: By addressing the convergence of BPM with various advanced technologies, this review advocates for interdisciplinary research that combines insights from fields such as information systems, operations management, and data analytics. This call for collaboration can lead to more holistic approaches to understanding and leveraging BPM in the context of Industry 4.0.

In conclusion, the integration of BPM with Industry 4.0 provides a foundation for organizations to enhance their processes, drive innovation, and improve overall performance. By leveraging the strengths of both BPM and Industry 4.0 technologies, organizations can position themselves for success in the digital economy, ensuring they remain competitive and responsive to the demands of the future.

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