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Lean-Enabled Digital Transformation: Industry 4.0 Technologies as Catalysts via Lean Practices

Mohamad Ali Mezher
Ph.D. Student
Adelaide Business School
The University of Adelaide
Adelaide, Australia
Mohamadali.mezher@adelaide.edu.au

Indra Gunawan
Associate Professor in Project Management
Adelaide Business School
Adelaide, Australia
Indra.gunawan@adelaide.edu.au

Sajad Fayezi
Associate Professor in Supply Chain Management
University of South Australia
The University of Adelaide
Adelaide, Australia
Sajad.fayezi@unisa.edu.au

Abstract

This study develops a theoretical framework explaining how Lean Practices (LP) mediate the relationship between Industry 4.0 Technologies (I4T) and Digital Transformation (DT) outcomes. It addresses a key gap in understanding how organizational practices influence the transformative impact of advanced digital technologies. Drawing on Benner and Tushman's process management trade-offs and Sambamurthy et al.'s IT-enabled capabilities, the study conceptualizes I4T, LP, and DT as interrelated constructs. Using an inductive Gioia methodology and cross-case analysis, it identifies mechanisms through which I4T and LP interact to drive transformation. The study finds four mechanisms by which specific I4T synergize with LP to enable DT across operational processes, customer experience, and business models. These are formalized into propositions that illustrate the mediating role of LP, the trade-offs involved, and key contingencies. The resulting framework shows how I4T contribute to DT through lean's socio-technical capabilities. This research contributes to IT-enabled transformation literature by showing that I4T's potential is only realized when combined with LP. It bridges efficiency- and innovation-oriented views and offers a multitheoretical explanation for successful DT. While qualitative, the study encourages future quantitative testing. Practically, it offers a roadmap for aligning digital technologies with lean practices to achieve more effective transformation.

Keywords
Industry 4.0 Technologies; Lean Practices; Digital Transformation; IT-enabled Capabilities; Case Study

1. Introduction

In today's volatile business world, adapting to digital technologies is a matter of survival. Former Cisco CEO John Chambers cautioned that "at least 40% of businesses will die in the next 10 years" if they fail to embrace new tech (Ross 2015). This urgency fuels interest in Industry 4.0, a suite of technologies driving smart automation and connectivity (Hermann et al. 2016). Industry 4.0 technologies (I4T) shift firms from rigid, centralized production to flexible, digitized operations across value chains. Adopting these tools triggers Digital Transformation (DT), redefining processes, customer experiences, and business models (Westermann et al. 2014).

DT success hinges on more than technology; it demands organizational alignment. Amazon leverages stakeholder feedback to steer its DT efforts (Amazon 2022), while Microsoft emphasizes employee training to unlock tech potential (Microsoft 2022). Technology isn't a cure-all; it requires cultural and operational shifts to deliver. Lean Management amplifies this digital evolution. Born from the Toyota Production System, lean eliminates waste and maximizes value via "hard" practices (e.g., just-in-time) and "soft" ones (e.g., employee empowerment) (Shah and Ward 2007; Bortolotti et al. 2015). Lean's problem-solving ethos ensures employees master digital tools, processes integrate automation, and stakeholder input shapes improvements, aligning tech with business goals.

While I4T and Lean Practices (LP) seem synergistic, research on their combined role in DT is fragmented (Rossini et al. 2021). Studies often explore them separately, focusing on factory-level gains (Belhadi et al. 2021; Kiris et al. 2023; Skalli et al. 2024). "Lean 4.0" research suggests mutual benefits, yet socio-technical dynamics and broader DT outcomes are underexamined (Saha et al. 2023; Nakandala et al. 2024). Their interplay across diverse contexts remains unclear.

Tensions complicate integration. Lean seeks simplicity and waste reduction, while I4T bring complexity and automation (Kagermann et al. 2011). Lean's standardization might curb digital flexibility, prompting questions: Do I4T enhance lean, or redefine it? Does lean channel digital investments into DT? What trade-offs arise?

We propose LP mediate I4T impact on DT, drawing on IT-enabled and dynamic capabilities theories. I4T alone don't guarantee value; they need lean's socio-technical framework to translate potential into results (Sambamurthy et al. 2003). This echoes Benner and Tushman's (2003) productivity dilemma: lean excels at exploitative efficiency but may hinder exploratory innovation unless paired with adaptive tools. I4T resolve this by infusing lean with data, flexibility, and connectivity, blending exploitation and exploration. Lean, in turn, grounds tech in disciplined improvement, ensuring alignment with objectives.

We tested this through a qualitative study of five firms integrating I4T and lean across industries. Using an exploratory, theory-building approach, we uncovered how their interplay drives DT, identifying mechanisms and trade-offs.

The paper proceeds as follows: The Theoretical Framework defines constructs and relationships. Methodology details our case-study design and analysis. Findings present four themes on I4T-lean integration, with propositions on mechanisms and contingencies. Discussion synthesizes insights, refines the framework, and offers implications. We conclude with contributions, limitations, and future research paths.

2. Theoretical Framework: Industry 4.0, Lean, and DT

Industry 4.0 marks the fourth industrial revolution, driven by advanced manufacturing and digital technologies. Coined in 2011 by a German government initiative, it has gained global traction (Kumar et al. 2020). Though over 100 definitions exist, a unifying theme is the use of cyber-physical systems for real-time communication, automation, and data exchange across value chains. We adopt Leyh et al.'s (2016) definition: "Industry 4.0 describes the transition from centralized production towards one that is very flexible and self-controlled. Within this production, the products and all affected systems, as well as all process steps of the engineering, are interconnected in real time."

In practice, I4T include IoT sensors, cloud computing, big data analytics, AI, robotics, and augmented reality. These tools enable real-time visibility, task automation, predictive insights, and enhanced connectivity within and beyond firms (Khin and Khee 2022; Abiodun et al. 2023). Viewed as digital "options," I4T offer agility and innovation potential (Sambamurthy et al. 2003). Yet, their value depends on implementation—technology alone doesn't guarantee success; it requires integration into organizational processes.

2.2 Lean Practices

Lean management maximizes customer value by eliminating waste and reducing process variability (Womack et al. 1990; Shah and Ward 2007). Originating from the Toyota Production System, lean spans industries with "hard" practices (e.g., just-in-time, kanban, jidoka) and "soft" practices (e.g., employee involvement, kaizen, supplier collaboration) (Bortolotti et al. 2015). Together, these form a socio-technical system focused on efficiency, quality, and continuous improvement (Hernandez-Matias et al. 2020). Lean targets waste, non-value-adding activities, using tools like value stream mapping, the "5 Whys," and frontline empowerment. It fosters a culture of "learning by doing," refining processes relentlessly. This continuous improvement capability equips lean firms to adopt I4T smoothly, leveraging standardized workflows and engaged employees. Studies suggest lean and I4T complement each other, with lean amplifying tech impacts while aligning deployments with customer value (Belhadi et al. 2021). However, lean's focus on incremental improvement and efficiency (exploitation) has raised questions about its compatibility with innovation. According to Benner and Tushman (2003), process management practices like lean are highly beneficial in stable environments for refining current operations, but they can be "fundamentally inconsistent with all but incremental innovation and change." In other words, an organization overly focused on lean efficiency might under-invest in exploratory, innovative activities – this is part of the productivity dilemma. We return to this issue when considering lean's interaction with digital innovation.

2.3 Digital Transformation

DT is the strategic use of digital technologies to overhaul operations, customer experiences, and business models (Vial 2019). Beyond mere IT adoption, DT entails organization-wide change, rethinking value delivery through automation, data-driven engagement, or new digital offerings. Many scholars describe DT as a process of moving an organization from a current state to a desired future state through digital means, often characterized as a form of organizational change management (Ghobakhloo and Iranmanesh 2021). Key dimensions of DT commonly discussed include (Morakanyane et al. 2017): Operational Process Transformation (improving internal processes through digitization and automation), Customer Experience Transformation (using digital tools to enhance customer interactions and value), and Business Model Transformation (innovating the firm's value proposition and revenue model enabled by digital technology). We treat successful DT as the desired outcome in our framework – manifested when a company sees significant improvements or innovations in operations, customer value delivery, or business scope due to digital technology use. We also remain cognizant that DT success is multidimensional: a company might excel at operational digitization but still be early in transforming its business model, for example. Lean's role may vary across these dimensions (something our propositions will reflect). Crucially, we distinguish digital technology adoption from DT: installing new IT (like IoT devices or software) is not DT by itself; DT is achieved when those technologies lead to new ways of working or competing (i.e., actual organizational transformation).

2.4 Lean as a Mediator between I4T and DT

Bringing together the above definitions, we theorize that LP mediate the relationship between I4T and DT outcomes. Figure 1 (conceptual framework) illustrates this idea at a high level: I4T influence DT outcomes primarily through their effect on lean practice capabilities. In essence, advanced technologies enable or enhance certain LP, which then drive transformations in operations, customer experience, or business models. Without lean, technology might not translate to full value; without technology, lean might be limited to incremental gains. Our framework posits that it is the interaction of I4T and lean that produces the most substantial DT results. This perspective builds on the IT-enabled organizational capabilities literature (Bharadwaj 2000; Sambamurthy et al. 2003), which asserts that IT generates business value through intermediate capabilities (like agility, knowledge management, or process excellence) rather than through direct effects. Here, LP constitute those intermediate capabilities. I4T provide raw digital potential (data, connectivity, automation), but whether that potential leads to transformation depends on organizational practices. A company deeply grounded in lean is likely to better capitalize on new tech – for instance, by quickly incorporating IoT data into waste-reduction efforts or using analytics to enhance customer value – whereas a company lacking process discipline might implement the same tech without seeing substantial benefits. A theoretical nuance in our framing is the classic exploitation vs. exploration tension (Benner and Tushman 2003). Lean is traditionally associated with exploitation – refining current operations for efficiency – and excessive focus on lean has been criticized for potentially suppressing exploration and innovation. However, we argue (and later demonstrate) that when modern digital technologies are introduced into a lean system, they can inject exploratory elements. For example, big data analytics can uncover new customer trends or process insights (a form of exploration), and AR tools can foster new ways of working and learning. Conversely, lean provides a structure to harness these exploratory "sparks" and integrate them into operations sustainably. In summary, our theoretical framework posits that I4T and LP function as

complementary forces in driving DT. Advanced technologies need the guiding hand of process practices to yield transformation, and LP can achieve far greater impact when augmented by digital tools. Answering how, specifically, this happens (the mechanisms), and under what conditions, is the goal of our empirical study.

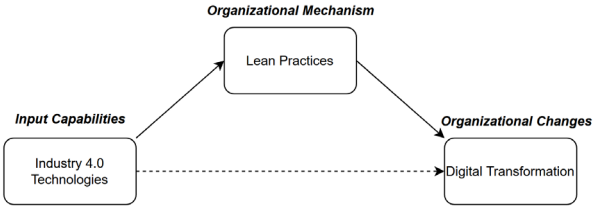

Figure 1. Lean-Enabled Digital Transformation

3. Methodology

3.1 Research Design

To explore the interplay between I4T, LP, and DT, we adopted a qualitative, multiple-case study methodology (Eisenhardt, 1989; Yin 2009). A case study approach is appropriate for our research question because we are examining a complex, under-theorized phenomenon in a real-world context. Specifically, how and why the combination of advanced technologies and organizational practices yields transformation outcomes. Case studies allow us to capture rich details of organizational processes and to uncover causal mechanisms that might be overlooked in a purely quantitative approach. Moreover, prior research on DT and lean has often been quantitative and isolated; thus, an in-depth qualitative approach provides the needed contextual insights and theory building to complement existing work. We followed Eisenhardt's (1989) guidelines for building theory from cases, as well as Yin's (2009) principles for case study rigor (construct validity, internal validity, external validity, reliability). To strengthen validity, we triangulated data sources and sought both literal replication (similar results in similar contexts) and theoretical replication (different results for predictable reasons) across our cases (Yin 2009). Our goal was not statistical generalization, but analytical generalization – to develop and refine theoretical constructs and propositions that could transfer to other contexts. In addition to multiple company cases, we incorporated an expert interview for additional insight and validation, as described below.

3.2 Company Selection

We used theoretical sampling (Glaser and Strauss 2017) to identify companies likely to exhibit the phenomena of interest. Namely, those combining I4T and LP in transformation initiatives. Case selection criteria included: (1) active implementation of one or more I4T; (2) an established record of lean or continuous improvement initiatives; (3) clear evidence of transformation outcomes, such as efficiency gains, improved customer service, or digital business innovations, attributable to these efforts; and (4) variation in industries and transformation foci to maximize learning. We selected cases to provide both contrasts and complementarities (Eisenhardt, 1989), avoiding a homogeneous sample. We consulted industry reports and practitioner literature to identify a pool of high-profile candidates. From this, five companies were selected: a global sportswear manufacturer (Nike), a grocery retailer (Woolworths), an e-commerce/tech firm (Amazon), a fast-fashion brand (Zara), and an automotive manufacturer (Toyota). These exemplars were chosen based on public visibility, data richness, and alignment with our selection criteria. We also conducted an expert interview with a senior manager at an anonymized digital training platform to include a service-oriented perspective.

3.3 Data Collection

Our data collection drew from two main sources: secondary data and one expert interview. For the five focal companies, we systematically gathered publicly available materials, such as company reports, press releases, news articles, and industry case studies, using targeted keyword searches. These sources helped us build detailed narratives of each company's DT efforts, LP, and implemented I4T. We included quotes from executives, analyst reports, technical blogs, and quantitative indicators where available (e.g., Nike's RFID supply chain data or Amazon's data platform usage). Additionally, we conducted a one-hour interview with a senior manager from an anonymized online training company. This key informant provided firsthand insights into how I4T and lean were integrated in a service

context. The open-ended interview, based on our conceptual framework, explored specific tech projects, the application of lean practices, outcomes, and challenges. To enhance credibility, we triangulated across data sources, cross-verifying claims (e.g., reported efficiency gains) and using the interview to clarify ambiguities and contextual factors not evident in published materials. All data was organized by company and theme to support subsequent analysis.

3.4 Data Analysis

We conducted an iterative, inductive analysis combining thematic and cross-case comparative techniques, guided by the Gioia methodology (Gioia et al. 2013) and our initial conceptual framework. The process began with within-company coding, where each case was analyzed individually. First-order codes were developed using informants' language, then grouped into second-order themes and tentative aggregate dimensions linked to key mechanisms like operational improvements. Next, we refined the data structures, comparing themes across cases, merging similar concepts, and ensuring each was grounded in evidence. A consolidated Gioia-style data structure was created. In the cross-company comparison, we identified recurring and unique patterns across firms, revealing consistent combinations of themes and notable outliers. Throughout, we iterated with existing theory, assessing whether findings aligned with the role of Lean mediating technological impact, and considered alternative explanations. Finally, we developed propositions summarizing the mechanisms and outcomes, supported by evidence from multiple cases. Reliability was ensured through dual coding, discussion, and limited member checking. We also validated findings through feedback from an Industry 4.0 and Lean scholar, reinforcing the credibility of our inductive conclusions.

4. Findings

Table 1 provides a summary of the cases, highlighting the I4T deployed, the focal lean practice, and the primary area of transformation for each. Following the table, we delve into each mechanism in detail.

Table 1. Overview of Cases: Industry 4.0 Tech, Lean Practice, and Transformation Focus

Company (Industry)	Key I4T Implemented	Lean Practice Focus	DT Outcome Area
Nike (Apparel mfg.)	IoT (RFID sensors); Big Data Analytics	Value Stream Mapping (inventory flow); Customer Involvement (feedback data)	Operational Processes; Customer Experience
Woolworths (Retail)	Cloud Computing; Big Data; Robotics; System Integration	Employee Involvement (agile teams, training); Customer Involvement (feedback data); Supplier Involvement (partnership)	Operational Processes; Customer Experience; Business Model
Amazon (Tech/Retail)	Cloud Computing (AWS); Big Data Analytics	Customer Involvement (feedback loops via Qualtrics); Continuous Improvement	Customer Experience (data-driven personalization)
Zara (Retail)	IoT (RFID); Big Data Analytics	Value Stream Mapping (supply chain JIT); Customer Involvement (trend response)	Operational Processes; Customer Experience
Toyota (Manufacturing)	Augmented Reality (AR); IoT	Employee Involvement (training, quality circles)	Operational Processes (shop-floor improvements)
Online Training Co. (Services)	Cloud Platforms; Big Data; System Integration	Employee Involvement (digital skill training); Customer Involvement (learning feedback); Supplier Involvement	Operational Processes; Customer Experience; Business Model (platform services)

4.1 Real-Time Data and Value Stream Mapping for Operational Excellence

Across several manufacturing-oriented cases (Nike, Zara, Toyota) and even parts of retail operations (Woolworths), a common mechanism was the use of real-time data from I4T to enhance lean process mapping and waste reduction,

leading to significant improvements in operational processes. Essentially, digital technologies provided unprecedented visibility and predictive insights into operations, which lean teams then used to streamline workflows, reduce inventory buffers, and improve responsiveness. This resulted in what we term a *DT of operational processes*: the companies achieved faster, more efficient, and more agile operations than traditional lean or IT alone could accomplish.

Nike offers a vivid example (Celestin 2021). Facing supply chain disruptions and inventory imbalances (exacerbated by the pandemic), Nike invested in RFID IoT technology to track inventory in real time across its distribution network (Dhesi 2021). By tagging products with RFID chips and scanning them via IoT sensors at warehouses and stores, Nike could monitor over a billion units with 99.9% accuracy, dramatically improving inventory visibility. Lean practice comes into play as Nike's operations team used this data to perform value stream mapping and eliminate inefficiencies in inventory management – they identified where stock was piling up, where shortages occurred, and could pull inventory through the system as needed (analogous to a kanban system but now digitally enabled). The company also acquired a predictive analytics firm (Celect) to analyse the RFID data for demand forecasting. This allowed Nike to better match supply with demand (a JIT principle) and reduce overstock (waste). According to Nike's CEO, this capability to anticipate demand and adjust quickly became a competitive advantage (Grill-Goodman 2020). In effect, Nike's adoption of IoT and analytics led to a digitally transformed supply chain – inventory turns improved and customers saw fewer stockouts or delays (an operational and customer benefit) (Silver 2021).

Zara similarly used RFID (IoT) technology in combination with their lean fast-fashion model (Yip and Huang 2017). Zara has long been known for LP like JIT production and rapid inventory turnover to stores (Li 2009). By 2018, Zara invested in embedding RFID tags in every item and rolling out scanners in all stores and distribution centres (McDonald 2025). This digitization enabled real-time tracking of garments, significantly improving the accuracy of inventory records and the speed of replenishment. Lean teams at Zara integrated this technology into their *value stream*, achieving near *zero inventory variability* on the shop floor – items sold were quickly detected and replaced, and any inefficiencies (like misplaced stock or slow-moving items) were flagged by the system. One lean manager described that RFID provided "great visibility" into the precise location of each garment (Bjork 2014). The outcome was a more efficient and responsive operation: Zara could run with even leaner inventories and update styles in stores weekly, aligning with customer demand in almost real-time.

Toyota's case adds another dimension with Augmented Reality (AR). Toyota, renowned for lean, introduced Microsoft HoloLens AR devices to improve training and maintenance on the production line (Siegel 2022). AR is an I4T that overlays DT onto the physical world. In Toyota's pilot, trainers created AR guides for assembly tasks and could virtually position new equipment on the factory floor to plan layouts (Aung 2019). The lean practice here is jidoka/quality and employee involvement: operators receive hands-free, on-the-spot instruction (reducing mistakes and downtime), and they can call a remote expert who uses AR annotations to assist. By empowering employees with real-time knowledge and problem-solving tools, Toyota sped up the training process (new hires became proficient faster) and improved quality (issues were fixed immediately with remote guidance). This is operational transformation through a human-centric lens – combining lean's "go to Gemba" (see problems at the source) with AR's capability to literally show solutions at the source. The outcome was more efficient and adaptive operational processes, as any changes or improvements could be rolled out quickly via AR instructions.

Mechanism Summary: In all these instances, the mechanism can be summarized as: *Real-time data and advanced digital tools provide transparency and analysis of processes, which lean teams leverage to identify and eliminate waste, reduce variability, and continuously improve operations.* The result is a transformed process that is faster, more accurate, and more flexible than before.

We also note a trade-off/contingency: these improvements required significant investment in technology and training. Companies had to ensure employees trusted and could utilize the data/AR systems. Additionally, while efficiency improved, companies had to be careful not to lose the human intuition and creativity in improvement – for example, data might show a problem, but human lean experts still needed to devise a solution. The cases that succeeded (Nike, Zara) clearly had both strong tech and strong lean cultures. In less prepared organizations, dumping streams of data on a team without lean discipline might overwhelm rather than help. Thus, a contingency is the maturity of lean processes and data literacy in the workforce.

Proposition 1: I4T-driven visibility and analytics, integrated with lean process improvement practices, enhance operational capabilities and lead to a digital transformation of operational processes. In other words, organizations that combine real-time data technologies with lean waste-reduction methods achieve significantly improved efficiency, quality, and responsiveness in their operations (relative to those adopting technology alone), thereby digitally transforming their operational workflows.

4.2 Data Analytics and Customer Involvement for Enhanced Customer Experience

The second recurring pattern identified in our study involves the synergistic use of big data analytics and AI (I4T) with lean's customer-centric practices, particularly those centred around ongoing customer feedback, iterative improvement cycles, and an obsessive focus on value creation for the end user. This mechanism was most apparent in service and retail-oriented transformations, particularly in the cases of Amazon, Zara, Woolworths, and the Online Training Platform. Collectively, these organizations exemplified how data-driven technologies, when combined with lean thinking, can drive significant transformation in customer experience. The result is a form of DT in which customer-facing processes are not only enhanced through technology but also shaped and refined by LP that prioritize eliminating non-value-adding activities and aligning processes with customer-defined value.

Amazon offers perhaps the clearest illustration of this mechanism in action. Known for its "customer obsession" ethos, Amazon's philosophy echoes lean's principle of delivering maximum value to the customer while minimizing waste. In our analysis, Amazon's collaboration with Qualtrics, a customer experience management platform, provides a compelling example. Amazon Web Services (AWS) partnered with Qualtrics to host their systems on the AWS cloud, while also leveraging Qualtrics' customer feedback tools internally (Amazon 2021). This dual arrangement enabled Amazon to gather and analyse large volumes of customer feedback in real time, with cloud infrastructure providing scalability and seamless integration.

LP in this context were embodied by the company's systematic use of customer feedback as a vital input for process improvement. For example, when a customer service interaction received a low satisfaction rating, Amazon's systems could instantly flag the issue and trigger a review or resolution process. This rapid feedback loop allowed Amazon to identify pain points and implement fixes quickly, improving overall service quality. The use of big data analytics enabled hyper-personalization, while the lean discipline ensured that improvements targeted true customer value. From a customer's perspective, this resulted in quicker issue resolution, more accurate product recommendations, and a sense that Amazon "understands" their needs.

Woolworths, one of Australia's leading retailers, also demonstrated this mechanism through its integration of advanced analytics into its customer engagement strategies. Leveraging data from its Everyday Rewards loyalty program (with over 13 million members) and digital shopping behaviors, Woolworths developed a "360-degree view" of its customers (TCS 2024; Woolworths Group 2022). Guided by its internal lean philosophy, branded as "Lean Retail", the company focused on delivering customer-defined value through service, pricing, and convenience. Data analytics helped personalize promotions, inform store layout decisions, and power online recommendation engines, all with the goal of minimizing customer "waste" (e.g., time spent searching or navigating irrelevant offers).

Additionally, Woolworths deployed AI-powered chatbots to streamline digital customer service interactions, and launched the ConnectedX platform through WooliesX to integrate customer data across channels. These efforts not only improved operational efficiency but also delivered a more seamless and personalized customer journey. Weekly app usage grew significantly (63% YoY in FY22), suggesting that customers responded positively to the data-enhanced, lean-driven experience (Woolworths Group 2022).

Zara, long known for its lean, just-in-time (JIT) model, added a digital layer to its customer engagement during the COVID-19 pandemic. With in-store traffic down, Zara relied on big data analytics from digital sources, such as website browsing behaviour and social media engagement, to gauge shifting customer preferences. This digital feedback loop became a new channel for "listening to the customer," a practice Zara had historically applied via store manager reports and direct customer feedback. The company used this data to make rapid adjustments to design and production decisions, allowing it to sustain its fast-fashion model even during a period of physical disruption (Shabir and AlBishir 2021). By merging lean responsiveness with digital data insight, Zara was able to maintain high levels

of customer engagement and satisfaction, effectively transforming its customer experience process under challenging conditions (Inditex 2020).

Our interview with a senior manager at a digital training platform highlighted a similar mechanism in a service-oriented context. The platform used real-time analytics to track learner progress and collect feedback, which informed ongoing course refinement. Modules with low engagement or poor feedback were either improved or removed, akin to lean waste elimination, while high-demand topics were expanded. Integration with a new cloud-based Learning Management System (LMS) supported rapid rollouts of updates in lean/agile cycles, with new content delivered every few weeks. According to the interviewee, these practices significantly improved learner satisfaction and completion rates, demonstrating how I4T and lean together enhanced the customer (learner) experience in a digital service environment.

Mechanism Summary: The mechanism here is: *Advanced analytics and data platforms capture rich customer data (needs, behaviours, feedback), and organizations practicing lean customer involvement utilize this data to iteratively improve and personalize the customer experience.* By quickly identifying what customers value and what they consider waste (e.g., unwanted features, delays, errors), companies can digitally reconfigure customer-facing processes. The transformation is seen in higher customer satisfaction, more personalized services, and often new digitally enhanced customer offerings (for example, Amazon deploying an AI-driven recommendation engine or Woolworths providing personalized wellness advice through their app – moving beyond just selling groceries).

Importantly, this mechanism underscores agility – frequent, small improvements in customer experience rather than occasional big overhauls. That aligns with a lean continuous improvement ethos, now turbocharged with real-time customer insight data. It also fosters a more customer-centric culture; employees start to rely on data to understand customer pain points, which can deepen empathy and responsiveness.

A trade-off/consideration here is privacy and trust: heavy use of customer data must be balanced with respecting customer privacy (a point the interviewee mentioned as well – they had to be careful with data usage policies). Another is analysis paralysis: organizations need the lean discipline to focus on actionable insights rather than drowning in data. The successful cases had a clear idea of what to measure and how to act on it (which lean thinking facilitated by focusing on value streams and customer value-add).

Proposition 2: Organizations that leverage big data analytics and AI in concert with lean customer involvement practices (continuous customer feedback and rapid response) effectively digitalize the customer experience, resulting in more personalized, responsive, and value-adding interactions. In simpler terms, by treating customer feedback as a critical input (a lean principle) and using advanced analytics to process that feedback at scale, firms can dramatically improve customer satisfaction and engagement, thereby achieving a DT in how they deliver value to customers.

4.3 Digital Tools and Employee Empowerment for Operational Innovation

The third theme centres on employees, specifically, how I4T are used to enhance employee involvement and capability development, which in turn drives operational improvements and innovation. Many cases pointed out that technology alone didn't transform processes until employees were empowered and skilled to use it. Lean emphasizes "respect for people" and engaging workers in problem-solving; here we see I4T like training simulators, collaboration platforms, and AI decision support enabling employees to contribute more effectively to transformation. The result is an organization that is *digitally transformed from within* – a workforce that is highly agile, skilled, and innovation-minded, leading to continual operational innovation (not just efficiency, but also adaptability).

One of the clearest examples is Toyota's use of Augmented Reality for training and support, which we touched on earlier (Siegel 2022). Traditional lean practice at Toyota involves on-the-job training, mentoring, and gradual skill development (often using paper manuals or instructor-led sessions). By introducing HoloLens AR, Toyota empowered its employees to learn and solve problems faster and more independently. For instance, maintenance technicians wearing AR glasses can see step-by-step instructions or diagrams overlaid on the equipment they are fixing. This means they rely less on calling a senior technician, and they learn by doing with guidance in real time. Also, when they face a novel issue, they can connect to an expert who remotely guides them using AR annotations, effectively

transferring knowledge on the spot. This significantly reduces downtime (improving operations) and builds employees' skills quickly (transforming the capability base of the company). Lean's notion of *jidoka* (stop and fix issues, and empower workers to do so) is enhanced by AR – any worker can tackle complex problems with digital assistance. The outcome is a more resilient and innovative operation, because employees are enabled to implement improvements or fixes without lengthy training delays or hierarchical approvals. One could say Toyota's operational knowledge is being "digitally augmented," expanding what each individual can do – a transformation of the work process.

Woolworths also strongly focused on the workforce aspect in its DT. It launched a "Future of Work" program investing $50 million in upskilling and reskilling employees in areas like data analytics, robotics, and agile ways of working (Woolworths 2021; Mitchell 2021). This was accompanied by technology deployments like an online learning platform (cloud-based) for employee training and actual automation (robotics in distribution centres) to handle rote tasks. The lean aspect is employee involvement and continuous learning – Woolworths recognized that to digitally transform, it needed engaged employees who are capable of adapting to new tools. By investing in their skills (a lean "respect for people" action) and using digital tools (e-learning, analytics training, etc.), they not only increased efficiency (as employees could now manage automated systems or use data in decision-making) but also cultivated a culture of innovation. Woolworths reported that this initiative helped redeploy staff into more value-adding roles and improved morale because employees felt equipped for the future (Crozier 2021). Operationally, processes became more agile: for example, software development processes were reorganized using cloud collaboration, which allowed engineers to switch projects easily (flexibility). In lean terms, they eliminated the waste of underutilized talent and siloed knowledge by empowering staff and flattening collaboration.

The Online Training platform case also highlighted employee involvement through technology. Internally, they used a cloud-based collaboration suite (SharePoint, etc.) to break down silos between content creators, IT staff, and customer support – making process improvement discussions transparent and inclusive (any employee could suggest a change on the shared platform, echoing a digital suggestion box). The interviewee credited this with speeding up internal improvements and aligning everyone with the transformation goals. Additionally, they used generative AI (an emerging I4T) to assist employees in creating new course content faster – here AI is a tool that amplifies employee creativity rather than replacing it. Lean thinking was applied by having employees review and fine-tune AI outputs, ensuring quality (a human-in-loop process improvement). This symbiosis of AI and human expertise led to a higher rate of course innovation on the platform.

Mechanism Summary: In these cases, the mechanism is: *Technology is used to empower and skill-up the workforce (not to deskill or replace them), which increases employees' capacity to innovate and solve problems, thereby improving operational performance and enabling continuous adaptation.* Lean's "people" dimension – training, involvement, delegation of problem-solving authority – is critical. The technology (AR, e-learning, AI tools, etc.) acts as a *force multiplier* for lean's human capital development.

A salient effect of this mechanism is a cultural transformation: companies become more learning-oriented and agile. Employees are not fearful of tech; instead, they embrace it as it helps them do their jobs better. This fosters a virtuous cycle where employees suggest further digital improvements, having experienced the benefits, thus sustaining the transformation.

However, a contingency to note is that the organization's leadership must genuinely commit to employee empowerment. If technology is introduced in a top-down, command-and-control way (e.g., monitoring workers without giving them benefits or input), it could breed mistrust and backfire. The cases that succeeded (Toyota, Woolworths) framed tech as support for workers, not surveillance or cost-cutting layoffs. This aligns with lean philosophy valuing people. So, the proposition will reflect that it's about *integrating tech in a way that complements and enhances human capabilities*.

Proposition 3: Organizations that adopt I4T to augment employee involvement and development, integrate technological and human capabilities to drive operational innovation and improvement. In short, by empowering employees with digital tools and skills, firms can achieve transformative operational gains – such as higher

productivity, quality, and adaptability – because employees become proactive agents of digital change rather than passive recipients.

4.4 System Integration and Supplier Collaboration for Business Model Innovation

The fourth mechanism pertains to extending transformation beyond the organization's four walls – using digital technologies to integrate with suppliers/partners and thus enable new or enhanced business models. Here, I4T like cloud platforms, APIs, IoT integrations are combined with lean principles of supplier involvement and collaboration to blur organizational boundaries and co-create value. The outcome is often a business model transformation, where companies offer new services or enter new markets by leveraging a digitally connected supply chain or partner network. A prime example is Woolworths' "Healthy Life" initiative. Woolworths partnered with a pharmacy chain (SuperPharmacy) to launch a new health and wellness platform offering prescription fulfillment, telehealth consultations, and wellness products (Woolworths 2022). This is a new business model for Woolworths, extending beyond groceries into healthcare services – essentially moving towards being a one-stop shop for health needs. How did they enable this? Through system integration technologies: they connected their IT systems with SuperPharmacy's systems to allow things like e-prescriptions to flow between the companies, and used cloud computing to host this integrated service. Lean's supplier involvement is reflected in the close collaboration – Woolworths treated SuperPharmacy as a partner in value delivery, aligning processes and sharing data. The integration was seamless enough that customers could order on Woolworths' platform and get fulfillment via SuperPharmacy without friction. The lean concept of extending the value stream to suppliers is evident: they created a joint value stream for health services. The result was the evolution of Woolworths' business model – they now provide a service (health and wellness) that goes beyond retail products, which diversifies their revenue and increases customer lock-in. This kind of transformation is enabled by digital tech (which makes such integration feasible at scale) but also by lean thinking (which emphasizes long-term supplier partnerships and trust, essential for sharing systems and data). The Online Training platform case too had an element of this: they integrated their Learning Management System with corporate clients' HR systems to offer training to those clients' employees seamlessly. By doing so (through cloud APIs), they essentially entered a B2B2C model (serving other companies' employees) rather than just direct B2C education. The lean aspect was working closely with client organizations to tailor and integrate – essentially treating client IT departments as part of the extended value chain. This allowed them to scale their reach and embed their service into client workflows (which is a business model shift from just selling courses to individuals to being a corporate training partner).

Mechanism Summary: The mechanism can be described as: *Digital integration technologies enable firms to tightly connect and coordinate with suppliers/partners, and when guided by lean collaboration principles (joint problem-solving, shared information, mutual trust), this extended network can deliver new forms of value to customers, effectively transforming the firm's business model or scope.*

In lean terms, it's expanding the concept of value stream beyond the organization – something lean literature calls "lean supply chain" or "extended lean enterprise." I4T makes this extension far easier (through real-time data sharing, cloud collaboration, IoT tracking across company boundaries). The synergy allows innovations like integrated services, platforms, or ecosystem-based models. A key contingency here is the strength of partnerships. If supplier relationships are adversarial or arms-length, simply integrating systems might not yield innovation; partners might not fully commit or share critical data. Lean teachings about selecting a few dependable suppliers and forging long-term relationships are relevant – Woolworths didn't partner randomly; they chose a credible pharmacy and built a program together. Thus, trust and strategic alignment are crucial. Additionally, not all industries allow easy partner integration (e.g., regulatory issues in health had to be managed in Woolworths' case).

Proposition 4: Organizations that utilize digital integration technologies (e.g., cloud platforms, IoT connectivity) to enhance collaboration with suppliers and partners can co-develop new value propositions, digitally transforming their business models through extended lean value streams. In essence, by working closely with partners via digital connectivity (and applying lean principles of waste reduction and value focus across organizational boundaries), firms can create new services or business lines that would be difficult to achieve alone, thus undergoing a form of business model innovation.

Together, these four propositions encapsulate our empirical insights on the mediated effect of lean between I4T and DT. In all cases, the adoption of I4T did not operate in isolation; it was the interplay with LP — whether in processes,

customer engagement, human resource development, or supplier collaboration — that actually produced the transformative outcomes. Figure 2 in section 5.2 (updated conceptual framework) illustrates these relationships, highlighting how different LP mediate different technology impacts leading to specific DT outcomes, and showing the overarching mediated model. In the next section, we discuss the implications of these findings for theory and practice, and how our framework contributes to bridging literature on IT-enabled capabilities and process management in the context of DT.

5. Discussion

5.1 Theoretical Contributions

First and foremost, our work reinforces and extends the IT-enabled capabilities perspective (Sambamurthy et al. 2003; Bharadwaj 2000) in the specific context of I4T and lean. Prior research in IS has argued that IT alone is rarely a direct source of competitive advantage; instead, IT contributes by enabling complementary organizational capabilities which then lead to performance gains. We provide concrete empirical evidence for this in the domain of I4T: Industry 4.0 technologies (IT) enhanced various lean capabilities (a firm's ability to continuously improve processes, engage customers, empower employees, integrate suppliers), and these enhanced capabilities were what directly produced transformation outcomes. This mediated path helps explain the mixed results in studies that looked for direct effects of digital tech on performance – firms that reported success were likely those that had the right process capabilities in place. By explicitly identifying lean as a key mediator, we add specificity to the IT business value literature. In particular, we highlight different *types* of capabilities: process efficiency (for operational excellence), sensing/responding (for customer experience), human capital agility (for internal innovation), and network collaboration (for business model extension). These map well to dynamic capabilities needed in the digital era, suggesting that lean can be viewed as a dynamic capability when infused with digital tools.

A significant theoretical insight from our study is how the combination of I4T and lean can help organizations navigate the classic tension between exploitation and exploration (Benner and Tushman 2003). Lean is traditionally associated with exploitation (refining current operations), and excessive focus on lean has been criticized for potentially suppressing exploration and innovation. However, our cases show that when modern digital technologies are introduced into lean systems, they can inject exploratory elements – for example, big data analytics enabling discovery of new customer trends (a form of exploration) or AR tools fostering new ways of working. Conversely, lean provides a structure to harness these exploratory sparks and integrate them into operations sustainably. In effect, I4T + Lean create a form of "ambidexterity on the fly" within processes: processes become more efficient *and* more adaptable simultaneously. For instance, Zara's use of data (exploration) with JIT (exploitation) let them innovate their product line continuously without sacrificing efficiency. This suggests that organizations might not always need separate structures for exploration (as strict ambidexterity theory would argue); if managed well, digital-lean integration allows exploration *within* operational processes. We contribute to theory by providing a nuanced view of the productivity dilemma: rather than being at odds, lean and digital tech can be configured to support each other. Lean's emphasis on removing waste can actually free up resources for innovation, and digital innovation can target pain points identified by lean analysis, creating a virtuous cycle. We do caution, however, consistent with Benner and Tushman (2003), that if a firm pushes lean to the extreme without openness to new technologies or feedback, it could become too rigid. The sweet spot is an integrated approach – what one might call "Lean DT" – combining the best of exploitation and exploration.

Another contribution is the clarification of constructs in a domain where buzzwords abound. We provided refined definitions for Industry 4.0, lean, and DT, drawing from authoritative sources. This is valuable for researchers, as terms like "digitalization" and "DT" are sometimes used loosely. By distinguishing DT as holistic organizational change (with radical impact) and Lean as a socio-technical system for continuous improvement, and then showing how they interact, we offer a clearer conceptual model. Notably, we delineate *technology* (I4T) from *transformation outcome* (DT), with *LP* forming the linking processes. This helps avoid conflating mere technology adoption with true transformation. A company isn't "digitally transformed" just because it installed IoT devices; transformation occurs when those devices lead to new ways of working or delivering value, which, as we argue, happens via lean-enabled changes.

Our work also contributes to lean management theory by demonstrating the applicability of LP in digital and service contexts. Lean originated on factory floors, but we saw its core ideas (waste elimination, variability reduction, stakeholder involvement) effectively applied to service industries. This supports the generalization of lean as a

management paradigm beyond manufacturing. It also suggests that lean's "soft" side (engagement, learning culture) is especially critical in DT, aligning with socio-technical systems theory which posits that technology implementations must be accompanied by parallel social-system changes (Trist and Bamforth, 1951). We give empirical backing to that: every case that succeeded did so by addressing people and process, not just technology.

The four propositions we developed are theoretically significant because they pinpoint specific mechanisms and contingencies that future researchers can test or explore further. For example, Proposition 1 (I4T + VSM → operational DT) can be tested in operations management studies by measuring the degree of IoT implementation, the rigor of process mapping, and resulting process performance. Proposition 2 suggests a moderating role of customer feedback loops in how analytics improve customer experience outcomes – future work could examine interaction effects between data analytics capability and customer-centric culture on customer satisfaction metrics. Proposition 3 implies that the effect of tech on operations is mediated by employee engagement; HR or IS scholars might investigate how digital training programs influence IT project success. Proposition 4 posits that partner integration leads to new revenue models; strategy researchers could look at firms that opened platforms to third parties to see if lean-like partnership governance influenced their business model innovation success. In sum, our propositions provide a foundation for more granular theory-testing in the MIS and operations fields regarding DT.

5.2 Updated Conceptual Framework

Based on our findings, we present an updated conceptual framework in Figure 2. The framework illustrates:

- Industry 4.0 Technologies – encompassing technologies that provide new capabilities (real-time data, automation, connectivity).
- LP (centre mediators) – categorized into four groups corresponding to our themes: (a) Lean Process Improvement (e.g., value stream mapping, waste elimination); (b) Lean Customer Engagement (e.g., feedback integration, customer-defined value); (c) Lean Employee Empowerment (training, involvement, kaizen); (d) Lean Supplier Collaboration (long-term partnerships, integrated supply chain).
- DT Outcomes (right side) – categorized as: (a) Transformed Operational Processes (efficiency, agility); (b) Transformed Customer Experience (personalization, responsiveness; (c) Transformed Business Models (new services, platform-based models, extended value proposition).

Arrows in the model show I4T influencing DT primarily through the lean practice mediators, rather than directly. Each lean mediator is linked to a specific primary DT outcome (as per our propositions), but we also acknowledge secondary links (for instance, empowering employees also positively affects customer experience through better service, though our proposition focused on operations). Crucially, the framework includes feedback loops: as DT progresses, it can reinforce LP. For example, a successful operational improvement might free up resources and increase trust in lean methods, prompting further lean initiatives (continuous improvement loop). Similarly, improved customer experience yields more feedback data, which can further refine processes. These feedback loops align with the idea of coevolutionary adaptation from Sambamurthy et al. (2003) – the firm learns and adapts iteratively. Another element in the framework is contingencies or moderators, shown as contextual factors around the arrows. Based on our discussion: organizational culture (especially openness to change and data-driven decision making) can moderate the effectiveness of Mechanisms 1 and 3; data governance and privacy considerations can moderate Mechanism 2 (if data use is too intrusive, it could backfire on customer experience); and partnership strength can moderate Mechanism 4 (weak partnerships might fail to produce new business value even with integrated systems). Environmental factors like industry uncertainty could also moderate how much exploration vs. exploitation a firm should emphasize. While our study did not formally test these moderators, we include them to guide future research and to indicate that our propositions likely hold more strongly under certain conditions. In summary, the updated framework offers a holistic yet granular map of how I4T and lean together produce DT. It advances the initial conceptual model (which posited simply "I4T → Lean → DT") by detailing which LP link to which aspects of DT and highlighting that transformation is multi-dimensional. Researchers and practitioners can use this framework as a diagnostic tool: to achieve a certain transformation outcome, what combination of tech and lean do we need? It also reminds us that neglecting the lean mediator (the middle layer) is likely why many DT fail – the framework visually enforces the idea that tech must be embedded in process and people changes (Figure 2).

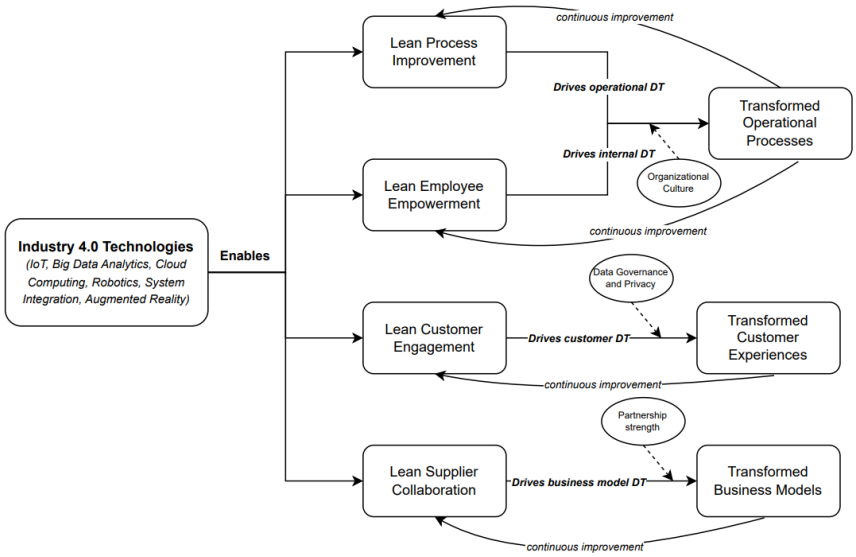

Figure 2. Updated Conceptual Model

5.3 Implications for Practice

Our findings yield important insights for practitioners managing DT initiatives. A clear implication is that investing in advanced technologies without concurrent investment in LP is unlikely to deliver desired results. Managers should therefore approach transformation as a dual effort: technology implementation and operational excellence programs hand-in-hand. For instance, if a company is rolling out IoT sensors on the factory floor, it should simultaneously train shop-floor teams in interpreting and acting on the new data (maybe using value stream mapping techniques). Our Nike and Zara cases showed that payoff comes when tech deployment is coupled with process redesign; otherwise, one might end up with lots of data and no improvement. Another practical insight is the significance of a continuous feedback culture. Whether it's customers or employees, creating feedback loops and acting on them quickly was a differentiator in our cases. Companies like Amazon that built strong mechanisms to capture voice-of-customer and integrate it into development cycles were able to enhance customer experience continuously. Tools for real-time feedback (Net Promoter Score systems, social media listening, etc.) combined with agile teams to address the feedback can replicate this success. Essentially, make customers and frontline employees key participants in the transformation, enabled by digital communication channels. The findings also suggest that skill development and change management are not side considerations but central to DT. Woolworths' extensive reskilling program is a model other firms can emulate. A practical recommendation is to establish a "Digital Academy" or similar internal program when embarking on DT, teaching both tech skills and lean/problem-solving skills. Lean techniques themselves can be taught company-wide so that when new tech arrives, employees naturally look for ways to use it to improve their work (instead of fearing it). This builds an internal momentum for change. In supply chain or multi-organization contexts, our results imply that firms should seek win-win partnerships and use digital platforms to integrate with partners. Rather than negotiating hardest on cost (old-school purchasing), lean suggests working together to remove waste in the chain. With cloud and blockchain etc., sharing information with suppliers is easier and can greatly cut lead times or inventory (waste). Managers should invest in integration projects (like Woolworths did) and treat key suppliers as extensions of their enterprise in transformation initiatives. This might involve joint IT systems, co-developing dashboards that show end-to-end supply chain status, etc. The payoff could be entering new markets or offering combined services which neither could alone. Lastly, our study has a message for top management: treat DT not as an IT project but as an enterprise-wide change program with a strong operational excellence component. Cross-functional leadership is needed – IT leaders should partner with operations/lean leaders. We saw that synergy at Toyota (IT working with manufacturing training dept) and at Amazon (AWS team with customer experience team). Many transformation efforts stall because they're siloed; our evidence underscores integration.

5.4 Limitations and Future Research

While our study yields valuable insights, it has limitations that open avenues for future research. We used a qualitative case approach with a limited number of organizations (five companies and one expert informant), which limits generalizability. The propositions we derived should be viewed as theoretical insights requiring further empirical testing on larger samples (e.g., surveys or quantitative analyses). Future studies could operationalize our constructs (e.g., "lean practice maturity" and "DT success") and statistically test lean's mediating role between I4T investment and performance outcomes. While we expect to find support for mediation, future work could also uncover where mediation breaks down or where other mediators (e.g., organizational culture or structure) play a role. A potential success bias is another limitation. Our cases mostly showcased positive outcomes; we did not deeply examine failed transformations. Future research could explore cases where similar technologies were adopted without lean, or where lean was present but not modern tech, to better isolate effects. A longitudinal study could also track transformation efforts over time, capturing micro-dynamics through ethnographic methods. We did not delve into financial outcomes (e.g., ROI). While we qualitatively noted improvements (e.g., faster inventory turns), future research could quantify how much performance variance is explained by the I4T+lean synergy. Examining time and cost implications of lean–tech initiatives versus tech alone would also be valuable. Finally, future work could explore lean's role in other DT domains (e.g., agile teams, creative industries) and its interplay with other improvement methods like Agile, DevOps, or Six Sigma.

4. Conclusion

DT is not achieved by technology alone; it emerges from the fusion of new technologies with robust organizational processes and capabilities. Our study highlighted the pivotal role of LP as the conduit through which I4T translate into meaningful transformational outcomes. We contribute a nuanced theoretical framework that marries insights from technological innovation literature and process management literature. In essence, firms can overcome the efficiency-versus-innovation trade-off by leveraging advanced IT within a lean management system, effectively achieving both. The findings expand the concept of IT-enabled capabilities by concretely identifying lean capabilities as essential mediators in the digital era. For practitioners, this work underscores that achieving DT is as much about cultural and process transformation as it is about installing new IT systems. Leaders should cultivate a lean mindset in tandem with tech adoption, ensuring that people are engaged, processes are optimized, and value to the customer remains the north star.

In sum, our research offers both a caution and an optimism. The caution is that chasing the latest technology without accompanying process excellence will likely yield disappointing results – a pattern seen in many failed transformations. The optimism is that organizations with a foundation in lean (or those willing to adopt lean thinking) can significantly amplify the benefits of digital technology, driving transformative changes that are sustainable and hard for competitors to replicate. DT, when done through the lens of lean, becomes not a one-time leap but a continuous journey of improvement and innovation.

We hope this study spurs further scholarly exploration into integrated approaches for organizational change and provides actionable guidance for firms navigating the challenges of the fourth industrial revolution. The synergy of I4T and lean holds considerable promise – one that, if managed wisely, can enable organizations to thrive in an era of rapid technological change.

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