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Lean Thinking in Healthcare 5.0 Technologies: An Exploratory Review

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Abstract

Industry 5.0 introduces a combination of technologies to improve sustainability, resiliency, and human-centered applications in the manufacturing environment. Similar to Industry 5.0, Healthcare 5.0 integrates emerging technologies like Artificial Intelligence (AI), Internet of Medical Things (IoMT), Big Data, Drones & Robotics, Digital Twin (DT), 6G, cloud/edge computing, and nanotechnology. These technologies offer significant benefits to society focusing on human wellbeing, wellness monitoring, personalized healthcare services, and sustainability. However, Healthcare 5.0 faces its own set of unique challenges. To respond to these challenges, Lean principles offer an excellent set of tools to increase the impact of Healthcare 5.0 technologies by improving efficiency and productivity while eliminating waste. Therefore, the objective of this study is to examine the role of Lean principles in maximizing the impact of Healthcare 5.0 technologies. Our analysis indicates that AI is the core technology utilizing Lean principles, with robotics and DT also playing key roles. In contrast, nanotechnology has the least connection with Lean principles among the Healthcare 5.0 technologies examined. Overall, this study offers one of the earliest efforts investigating the integration of Lean principles with Healthcare 5.0 technologies, shedding light on their potential to advance healthcare.

Keywords
Healthcare 5.0, Industry 4.0, Lean Thinking, Lean Principles, Smart Healthcare Systems

1. Introduction
The journey of industrial evolution began in the late 18th century with the invention of steam engines and mechanized production. This evolution progressed to Industry 2.0 with the introduction of assembly lines and mass production. Later, the introduction of computer systems and automation in Industry 3.0 accelerated efficiency and process speeds in every aspect of the industry. Industry 4.0, however, marked a paradigm shift, integrating cutting-edge technologies such as Big Data, Artificial Intelligence (AI), Virtual Reality/Augmented Reality (VR/AR), Internet of Things (IoT), Cloud Computing, Additive Manufacturing (AM), Autonomous Robots, Cybersecurity and Digital Twin (DT), setting a new benchmark for technological advancement.

Building on the momentum of Industry 4.0, Industry 5.0 emerges as a fusion of sophisticated technologies and progressive organizational principles, emphasizing sustainability, resilience, and human-centric approaches in production systems. Mirroring this advancement, Healthcare 5.0 transforms patient care and smart healthcare systems, centering on human wellbeing and delivering advanced, personalized healthcare services. It aims at enhancing wellness monitoring, sustainability, affordability, and accessibility as seen in Fig 1. Despite its human-centric focus, Healthcare 5 faces distinct challenges that require a comprehensive and systematic approach to overcome.

Lean principles play a significant role in the manufacturing industry, yet their value is equally important within healthcare applications. Given that sustainability and waste elimination are crucial for the future development of emerging technologies in Healthcare 5.0, the integration of Lean principles will become inevitable. This integration not only facilitates waste reduction but also improves operational efficiency, patient care quality, and resource optimization, making *Lean Thinking* (Womack and Jones, 1997) a fundamental application for achieving sustainable healthcare systems.

1.1 Objectives

This paper discusses Healthcare 5.0 and its emerging technologies in smart healthcare systems from a broad scientific perspective. We aim to analyze the unique challenges faced by these technologies and evaluate them through the perspective of Lean Thinking. Therefore, we developed a relationship matrix that illustrates the extent of the relationship between Lean principles and Healthcare 5.0 technologies. This matrix will be constructed utilizing qualitative justification categories, including technology capabilities, relevance to Lean principles, implementation impact, innovative application, and cross-industry insights. As a result, our proposed assessment tool aims to demonstrate the degree to which the Lean principle should be integrated into Healthcare 5.0 technologies. Based on our assessment tool, we aim to guide the level of prioritization in Healthcare 5.0 technologies and their initiatives (Figure 1).

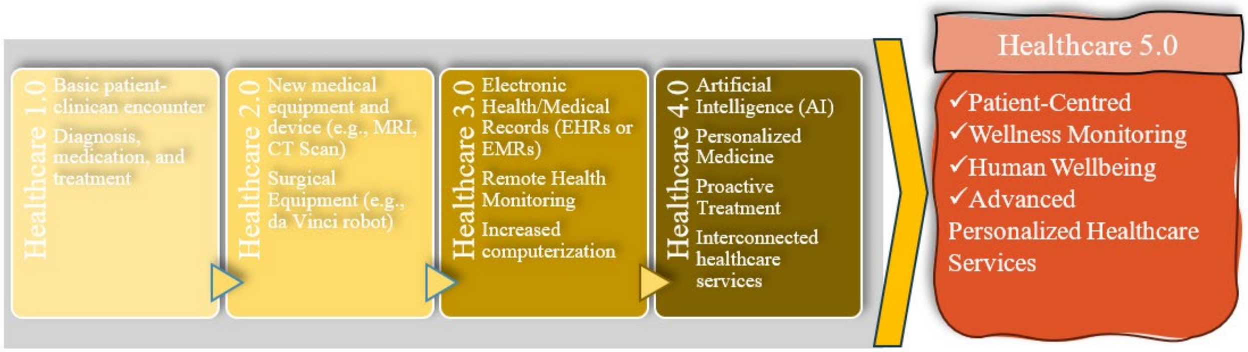

Figure 1. Historic Evolution of Healthcare 1.0 to Healthcare 5.0

2. Literature Review

Healthcare 5.0 represents a transformative integration of advanced technologies, including AI, IoMT, VR/AR & DT, 6G, Nanotechnology, Cloud/Edge Computing, Big Data, Blockchain, and Robotics & Drones, marking a new era in smart healthcare systems. As we have seen in Table 2, we also summarized some of the Healthcare 5.0 technologies and their respective applications in smart healthcare solutions.

Since Ivan Sutherland introduced the first head-mounted display in 1961 (Sutherland), ***VR/AR*** technologies have made significant strides, offering immersive and interactive experiences. These developments are supported by advancements in sensor, computing, and graphics technologies. As we have seen in Table 2, VR/AR systems are now increasingly used in healthcare operations such as surgical precision (Andrews et al., 2021), medical education (Mendes et al., 2020), and real-time remote surgeries. The integration of ***DT*** technology with VR/AR allows for the development of virtual replicas/twins of physical systems, including patient anatomy or surgical environments, providing a platform for training, simulation, and operation planning. This connection between VR/AR and DT technologies is very significant for achieving an efficient and patient-centered approach in Healthcare 5.0, helping frontline healthcare professionals to simulate and analyze medical procedures in a controlled virtual space before the actual surgical operations.

Nanotechnology is gaining attention for its cost-effectiveness and ease of use, showing great promise in smart healthcare applications. thanks to its practicality, nanotechnology made significant contributions in studies such as targeted drug delivery for neuroprotection, gene therapy, and alleviating the impact of COVID-19 (Vazquez-Munoz & Lopez-Ribot, 2020). Furthermore, nanotechnology's application in nanobiosensors and nanosensors opens more opportunities for its integration into smart healthcare systems (Vaghasiya et al., 2023), offering scalable and modular solutions especially beneficial to underserved regions. Lastly, nanotechnology can be utilized with the help of AM techniques to support rapid prototyping in research studies and increase modularity in smart healthcare applications.

The rapid advancement in large language models and other ***AI*** innovations aims to revolutionize smart healthcare systems. AI's integration into smart wearable devices and hospital infrastructure signifies a leap towards personalized healthcare, enhancing patient care through customized medication and treatment plans and thereby improving health outcomes. AI's role is significant in refining healthcare operations, including robotic surgeries, laboratory diagnostics, pathogen detection, and the use of medical imaging diagnostics (e.g., MRI, CT scan, X-rays), and gait analysis (Avdan et al., 2023). While AI is a cornerstone of Healthcare 5.0, it has not yet reached its full potential. The anticipated advancements in quantum computing are expected to exponentially improve AI's problem-solving capabilities, facilitating the processing of complex problems at unprecedented speeds compared to classical computers (Chauhan et al., 2022).

Compared to 5G technology as seen in Table 1, the integration of ***6G*** technology in Healthcare 5.0 promises to revolutionize smart healthcare through reliable, ultra-fast, and low-latency communication (Banafaa et al., 2023). This advancement is very important for supporting high-quality data transmission for remote monitoring, consultations, telemedicine, and even remote surgeries where every millisecond counts. The seamless connection between 6G and IoMT ensures connectivity for continuous patient monitoring and efficient data collection (Ahmad et al., 2022). Furthermore, 6G is capable of facilitating large-scale AI algorithms for diagnostic and predictive analytics, improving patient care through immersive AR/VR applications, and contributing to a more responsive and patient-centered healthcare environment.

Table 1. Comparison of 4G, 5G, and 6G technologies

KPIs	4G	5G	6G
Peak data rate	1 Gbps	10 Gbps	1 Tbps
Latency	100 ms	1 ms	0.1 ms
End-to-end reliability	99.9%	99.999%	99.9999%
Max Frequency	6 GHz	90 GHz	10 THz
AI	No	Partial	Fully
Autonomous Vehicle	No	Partial	Fully
Extended Reality (VR/AR)	No	Partial	Fully
Architecture	MIMO	Massive MIMO	Intelligent Surface

Note: *KPIs: Key Performance Indicators, and MIMO: Multi-input multi-output.*

Big Data harnesses a significant amount of information from electronic health records (EHRs), medical imaging, and wearable devices, offering a comprehensive perspective of patient health. Big data plays a crucial role in personalizing medicine, leveraging sophisticated AI applications to personalize treatments and care plans. By integrating AI with big data, medical professionals can predict disease outbreaks, monitor public health trends, and improve patient care strategies. Additionally, big data is instrumental in streamlining hospital operations, developing sophisticated algorithms (Avdan et al., 2024), and optimizing patient flow, positioning itself as a cornerstone for the development and advancement of Healthcare 5.0 technologies. Thanks to big data, healthcare systems can achieve a more efficient, effective, and patient-centered approach.

Table 2. Examples of Healthcare 5.0 tools, their functions, and additional details

Healthcare 5.0 Tools	**Functions and Additional Details**
Virtual Ward	Provides at-home care eliminating the need for hospitalization; reduces patient admission; improves access for the elderly population.
Humanoid Robots	Offers increased patient assistance 24/7; improves sterilization cutting human interaction; easier infectious disease control.
Drones	Enables rapid delivery of medical supplies; offers cost-effective and safe transportation; improves accessibility for underdeveloped regions.
Nanocarriers and Nanoparticles	Facilitates smart and targeted drug delivery; has a sanitizing effect on viruses.

Cloud/Edge Computing	Provides real-time communication, cost-effective; enables data recovery; reduces latency; enables telemedicine and remote patient monitoring.
VR/AR Devices	Supports remote healthcare services; improves medical training conditions for underdeveloped skills; increases visibility during non-invasive operations.
3D Bioprinting	Regenerates tissue and organs; improves personalized medicine conditions.
Nano-enabled Wearable Sensors	Enables remote health monitoring, and personalized healthcare services; offers real-time smart drug delivery in response to the patient's medical condition.
Ambient Assisted Living	Facilitates rapid emergency response and real-time health monitoring; improves the quality of life; automated medication system; reduces dependency.

Blockchain provides cutting-edge solutions to enhance data security and ensure data transparency in smart healthcare systems. This technology operates through a series of blocks that chronologically store data, functioning as an append-only structure (Mbunge et al., 2021). Blockchain-based healthcare applications range from EHRs and managing health insurance claims to pharmaceutical supply chain management and remote patient monitoring. As the need for data sharing increases along with advancements in generative AI and IoMT, Blockchain technology will stay crucial to Healthcare 5.0 technologies. It establishes secure, decentralized networks that meet the essential requirements of smart healthcare infrastructures, ensuring data privacy and integrity.

Cloud/Edge Computing brings scalable and cost-effective solutions, making it a game-changer for smart healthcare systems. These computing solutions are especially important for small to medium-sized enterprises where they don't have the capital to invest in expensive infrastructure (Masood and Sonntag, 2020), while larger corporates have the resources to build their own cloud environments. Cloud/edge computing is crucial for handling Big Data, including patient information management, disease prediction modeling, and disease tracking. It also improved telemedicine practices by enabling remote patient monitoring and consultations with healthcare professionals. Furthermore, cloud/edge computing supports IoMT devices and is key in building the infrastructure for modular and scalable Healthcare 5.0 technologies, offering a foundation for a more interconnected and efficient healthcare ecosystem.

Robotics and drones are increasingly becoming pivotal in healthcare delivery and the operation of smart healthcare facilities. The post-pandemic world has seen a surge in the adoption of autonomous technologies. The synergy of AI, IoMT, and VR/AR technologies has notably improved medical robot applications, from performing surgeries to delivering healthcare services, especially under infectious conditions (Di Lallo et al., 2021). Concurrently, drones, or unmanned aircraft systems, are utilized for the swift transportation of medical services, including drugs, blood products, and even organs (Scalea et al., 2021). The integration of robotics and drones into Healthcare 5.0 systems promises to significantly increase the efficiency, accessibility, and quality of healthcare services, revolutionizing patient care and operational logistics within healthcare settings.

The Internet of Medical Things (IoMT) is a specialized branch of the IoT aimed at healthcare technology. It connects medical devices and apps, creating a network that communicates with healthcare systems for more personalized and efficient care. IoMT enables telemedicine, predictive healthcare, and remote health monitoring, making it easier to manage patient health for health professionals. Examples of IoMT can be given as wearable health monitors like ECG and EMG devices (Avdan et al., 2023), personal emergency response systems (Stokke, 2016), and drones used for delivering medical supplies (Gupta et al., 2022).

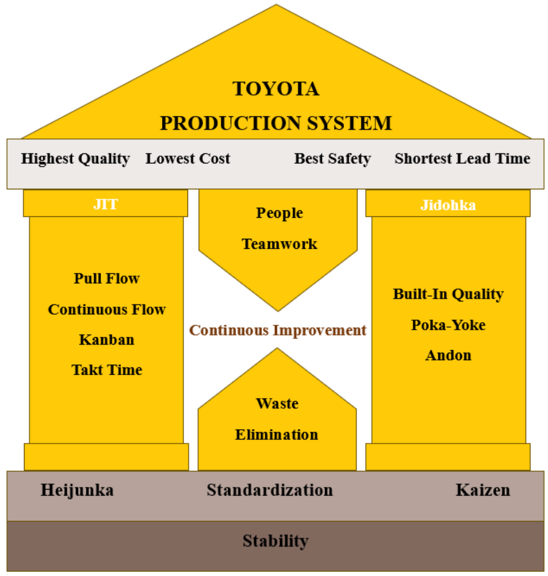

Figure 2. Toyota Production System (TPS) House

The concept of ***lean manufacturing*** originated from the Toyota Production System (TPS), developed by Taiichi Ohno, who is considered the father of TPS (Ohno, 2019). He also invented the term "Muda", which translates to "7 Wastes" in Japanese, including transportation, inventory, motion, waiting, over-processing, over-production, and defects (Womack et al., 2007). Additionally, some studies recognize an 8^{th} waste as a non-utilized talent. To eliminate waste, industries may follow the lean principles for continuous improvement (CI). These lean principles can be visualized in the TPS House, as shown in Fig. 2. The foundation of the TPS House is built on process stability and standardization, upon which businesses may construct their perspectives. Kaizen and Heijunka work together to level customer demand, reducing production fluctuations and preventing excessive product batching (Coleman and Vaghefi, 1994). On the right pillar, Jidohka (Automation) ensures high-quality standards by identifying defective products and facilitating necessary improvements/corrections to the production line. Poka-Yoke (error-proofing) and Andon are also other practices to strengthen the high-quality standards. The left pillar surrounds with Just-In-Time (JIT), Pull Flow, Continuous Flow, Kanban, and Takt time. These strategies synergize to meet customer demands on-time and efficiently while minimizing inventory, thus addressing one of the 7 Wastes. The objective of these two pillars is to achieve the highest quality and lowest cost with the shortest lead times, all while maintaining safe conditions for meeting customer demands. At the core of the TPS House lies the synergy of the people, teamwork, and a commitment to waste reduction, prioritizing continuous improvement in the processes.

3. Methods

After conducting a rigorous literature review (see Section 2) for Healthcare 5.0 and lean principles through Google Scholar, and other resources (e.g., IEEE, Scopus, and ProQuest), we identified a list of most commonly used lean principles and the key technologies utilized in Healthcare 5.0 applications. We selected the following keyword sets for the search: "healthcare 5.0 opportunities and challenges", "lean principles industry 4.0", "healthcare 5.0 lean principles", "lean industry 5.0", and "lean integration in industry 5.0". We didn't include the studies not written in English. Additionally, we only include peer-reviewed studies from journals, conferences, and workshops.

As a result, we adapted the 14 Lean principles with minor modifications from the study by Pakdil et al. (Pakdil et al., 2020) which were initially presented in the *Lean Thinking* "The Toyota Way" study by Krinjen et al. (Krijnen, 2007). Afterwards, we developed a relationship matrix by considering the rapid advancement of emerging technologies in Healthcare 5.0. As we have seen in Table 4 (see Section 4), this matrix is designed to assign weights (on a scale of 1-5, where 1 is the least impactful, and 5 is the most impactful) to the relationship between each lean principle and each Healthcare 5.0 technology. This matrix also reflects the potential impact or relevance of technology in improving or developing lean principles within smart healthcare settings. Additionally, we designed a justification matrix to demonstrate the various justification categories for each Healthcare 5.0 technology. Thanks to this justification matrix, we provide a qualitative insight into our rationale behind the value matrix assignments between lean principles and

Healthcare 5.0 technologies. As we have seen in Table 3 (see Section 4), the categories include (i) relevance to lean principle, (ii) technology capabilities, (iii) implementation impact, (iv) innovative application, and (v) cross-industry insights. In this justification matrix, we used a simpler qualitative scale, assigning High (H), Medium (M), and Low (L) to denote the extent of each Healthcare 5.0 technology's alignment with the justification categories.

For the relationship comparison between lean principles and Healthcare 5.0 technologies, we used descriptive statistics including mean and standard deviation. It is important to note that these results don't include any confirmatory statistical analysis. Nonetheless, these results offer a comprehensive summary of the literature on Healthcare 5.0 technologies and lean principles.

4. Results and Discussion

4.1 Exploratory Analysis between Lean Principles and Healthcare 5.0

One of the key features of Healthcare 5.0 technologies is their focus on sustainability, resilience, and human-centered applications, which is considered as a step forward of the predecessor, Healthcare 4.0 (Avdan & Onal, 2024). Meanwhile, lean production systems are prioritized the continuous improvement practices, employing lean principles to optimize processes. This approach ensures the delivery of high-quality services at the lowest possible cost to the customer. In the context of Healthcare 5.0, the customer is defined as "human". Given that Healthcare 5.0 places humans at the core of its applications, lean systems emerge as an ideal complement for providing high-quality and affordable services.

As we have seen in Table 3, AI, AM/3D printing, robotics, and DT were shown high relevance with each of the justification categories. Their extensive applicability in healthcare suggests that these technologies will play a major role among other Healthcare 5.0 technologies. Even though AI is already at the core of technological improvements, its integration into smart healthcare is expected to expand further (Saraswat et al., 2022). Lean principles, which aim to minimize hospital wait times, reduce medical errors, and enhance service quality, will be a strong driving factor in AI technology. Thanks to AI, lean principles may achieve faster lead times and higher quality care in healthcare systems (Chakraborty et al., 2023). Moreover, AI can benefit from Heijunka, the lean practice of production leveling, in minimizing excess inventory through more accurate demand forecasting and resource allocation. The effective implementation of AI in healthcare is dependent on access to big and high-quality data. Therefore, Big Data will be a critical support for AI-driven lean systems. Similarly, IoMT applications will grow at a faster rate with the help of advancements in AI. This growth will significantly benefit the wearable device sector by improving patient service quality. As we have seen in the manufacturing sector's success with IoT (Anosike et al., 2021), lean practices in healthcare, facilitated by IoMT integration, will streamline operations, reduce waste, and provide a continuous flow of healthcare services.

Table 3. Justification matrix between Healthcare 5.0 technologies and justification categories

Healthcare 5.0 Technologies	Relevance to Lean Principle	Technology Capabilities	Implementation Impact	Innovative Approach	Cross-industry Insights
Nanotechnology	M	M	L	H	M
AI	H	H	H	H	H
IoMT	H	H	H	M	H
VR/AR	H	H	M	H	M
Cloud/Edge Cmp.	H	H	H	M	H
6G	M	H	H	M	M
Big Data	H	H	H	M	H
AM/3D printing	H	H	H	H	H
Blockchain	H	M	H	M	M
Robotics	H	H	H	H	H
Drones	M	M	M	H	L
DT	H	H	H	H	H

In smart healthcare systems, AM undoubtedly plays a significant role by offering flexible production applications. It mitigates CI efforts by facilitating the elimination of 7 wastes while providing potential sustainable practices (Ghobadian et al., 2020). Additionally, AM is a great tool in organ printing (Scalea et al., 2021), which is a very hot topic in medical research studies, aiming to deliver high-quality services to patients. However, it is important to note that not all healthcare facilities have access to such advanced services. Despite AM's strength in our justification categories, lean principles were not as applicable as other Healthcare 5.0 technologies. Thus, we expect to see AM is a complementary tool for other Healthcare 5.0 technologies for the integration of lean principles in healthcare facilities.

Table 4. Relationship matrix between Healthcare 5.0 technologies and lean principles

	Healthcare 5.0 Technologies											
Lean Principles	Nano	AI	IoMT	VR/AR	Cloud /Edge	6G	Big Data	Add. Manuf. /3D	Block chain	Robotics	Drones	DT
VSM	2	5	4	3	4	3	5	3	4	3	2	5
Kaizen	3	5	4	4	4	4	5	3	3	4	2	5
SMED	2	4	3	3	3	2	4	4	2	5	3	4
5S	1	3	3	2	3	2	3	2	3	4	1	3
Heijunka	2	4	4	2	4	3	4	2	3	3	2	4
Jidohka	3	5	4	4	4	3	4	3	3	5	2	5
CI	3	5	4	4	5	4	5	3	4	4	3	5
JIT	2	4	4	3	4	5	4	3	4	3	3	4
Pull Flow	2	4	5	3	4	4	4	3	4	4	3	5
Waste Elimination	3	5	4	3	4	3	5	4	4	5	3	5
Kanban	1	4	4	2	4	3	4	2	4	3	2	4
Poka-Yoke	2	5	4	3	3	2	4	3	3	5	2	5
Standard.	3	5	4	4	5	4	5	4	4	5	3	5

In healthcare services, robotics is increasingly important, offering tools like service robots that help patients track their treatment and carry out diagnostic tests (Karabegović and Doleček, 2017). These robots also limit the need for face-to-face meetings between healthcare workers and patients, which is especially valuable during pandemic and disease outbreak conditions (Holland et al., 2021). Even though these robots need regular technical inspections, they work without fatigue and eliminate human errors, ensuring consistent and high-quality healthcare services. Robotics extends its benefits to healthcare logistics, speeding up service delivery and improving service quality. Robots equipped with inventory management and Kanban systems can effectively manage stock levels, avoiding overstocking and maintaining medical supplies are always available. This approach is a direct application of Lean's focus on JIT production, adapted to the healthcare settings. Additionally, robotic applications will support the standardization and stability efforts, which are the foundation of TPS house (see Figure 2). The standardization efforts can also be supported by 5S to organize the inventory rooms and SMED to reduce the setup time for medical operations. In surgical operations, robotic devices also improve health outcomes through telesurgery, allowing for less invasive procedures that are particularly useful in complicated surgeries. By applying Jidohka, or automation with a human touch, surgical robots increase accuracy and reduce risks, tackling the critical issue of medical errors that lead to 50,000 to 100,000 patient deaths each year (Bush, 2007). However, integrating AI and connecting these systems to cloud/edge computing services introduces a risk of cyberattacks. This is where Blockchain technology becomes crucial, improving security measures to protect against these threats (Ray et al., 2023). Blockchain's role is crucial, reinforcing the lean principles to build a secure and uninterrupted flow of information to provide robust data management practices as shown in Fig. 3. Blockchain enhances the protection of robotic systems against cyber threats, ensuring the reliability and integrity of patient data. This security measure supports the seamless operation of Healthcare 5.0 technologies, such as robotics, AI, IoMT, providing a strong foundation for these innovations to advance lean healthcare practices. In short, the strategic use of these technologies will support Lean principles in Healthcare 5.0 technologies by focusing on efficiency, quality, and patient-centered care.

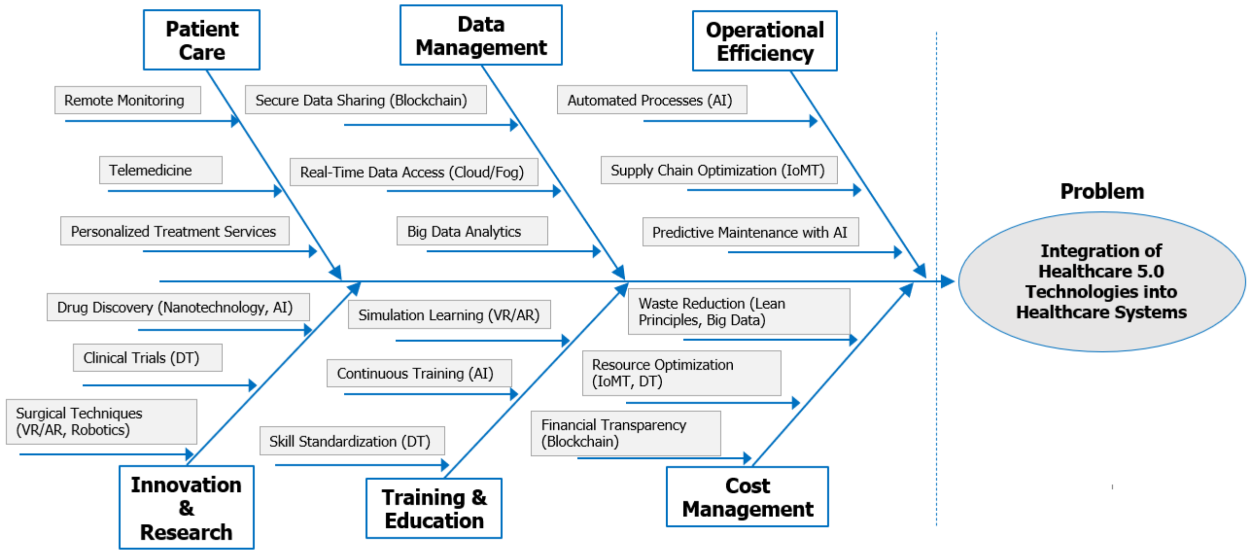

Figure 3. Cause-and-effect diagram for the Integration of Healthcare 5.0 Technologies into Healthcare Systems

In terms of nanotechnology in healthcare applications, it has the potential to significantly improve efficiency, a key goal of Lean principles. This efficiency can be systematically evaluated through VSM technique, which identifies and eliminates waste in processes. Beyond just efficiency, nanotechnology can increase the healthcare provider's competitive advantage and reputation by offering innovative solutions as shown in Fig. 3, and cutting-edge treatments that attract new patients (Elemure et al., 2023). However, it is also crucial to acknowledge that the impact of nanotechnology on certain operational metrics, such as data security, error rates, and flow processing, might be minimal. This means that while nanotechnology offers substantial advancements in patient care and treatment options, its direct influence on improving operational lean metrics may be limited. Consequently, the return on investment for nanotechnology can be lower than other Healthcare 5.0 technologies that more directly impact Lean operation improvements.

While drones have become a well-known delivery service for package delivery, their application in the delivery of medical products, including organs, presents unique challenges due to the critical nature of these deliveries. Drones offer the advantage of speed, yet their operational range is currently constrained by battery technology limitations (Maghazei and Netland, 2020). As a result, rural areas, that could greatly benefit from these services, face challenges in accessing drone delivery opportunities. This limitation prevents the broader applicability of drones for healthcare purposes. However, anticipated advancements in battery technology and improved connectivity could help for more extensive drone usage in the future. These developments would not only extend the drones' range but also improve their reliability, making them a great solution for Lean healthcare systems focused on reducing waste and improving service delivery.

Even though 6G doesn't exist yet, we expect to see significant changes in telemedicine and remote healthcare services, which will positively impact patient care outcomes as shown in Fig. 3. The expected benefits of 6G include reliable, ultra-fast connectivity, and low-level latency (see Table 1). These features aim to advance the healthcare applications in the field of robotics, IoMT, Cloud/Edge computing, and DT technologies, ensuring that high-quality services are delivered more efficiently to patients which is imperative for CI efforts (Padhi and Charrua-santos, 2021).

Thanks to VR/AR technologies, medical education has seen a great development leap. These efforts could have a good impact on improving surgical operation accuracies because of provide a great educational foundation for resident training (Godzik et al., 2021). These technologies also minimize workplace hazards and injuries, crucial in maintaining a safe and efficient healthcare environment (Marinelli, 2022). Therefore, VR/AR can make a good impact on CI, Kaizen, and standardization efforts (see Table 4 and Figure 3). It will also reduce waste such as time and resources for the training.

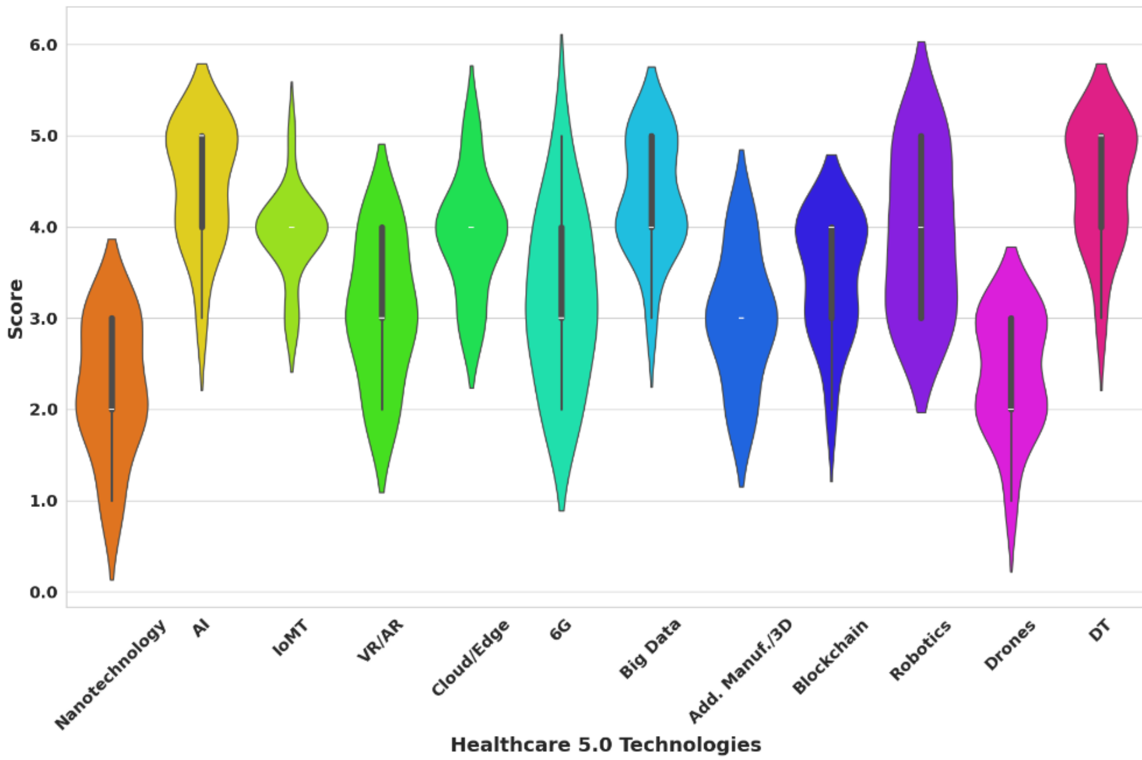

Figure 4. Average Lean score comparison among Healthcare 5.0 technologies

Overall, AI will be the most integral part of Healthcare 5.0 technologies involving *Lean Thinking* principles (see Figure 4). Robotics and DT technologies are expected to closely follow AI in their applications. in contrast, Nanotechnology may see the least integration effort with Lean principles. Meanwhile, IoMT, 6G, Blockchain, and Cloud/Edge Computing will play integral supporting roles for AI, Robotics, and DT technologies in the deployment of Lean strategies. Although AM technology has high relevance in our study (see Table 3), its role in Lean principles will not be as a primary driver factor but rather as a supplementary element supporting waste elimination and the delivery of efficient and high-quality services.

4.2 Economic Implications of Integrating Lean Practices with Healthcare 5.0 Technologies

From an economic and operational efficiency standpoint, the integration of Healthcare 5.0 technologies aims to significantly reduce the overwhelming demand for in-person doctor visits by improving telemedicine and remote monitoring capabilities. Wearable devices, for example, can measure critical health metrics such as ECG, blood pressure, and heart rate, utilizing continuous health monitoring outside of traditional clinical settings. These wearable devices are equipped to send real-time health data to healthcare providers. Then, AI-diagnostic systems through cloud/edge computing are used to detect health issues in the earlier phases.

The shift towards prioritizing disease prevention means fewer patients will require invasive surgeries, significantly reducing the load on hospital staff and resources. Moreover, the widespread adoption of telemedicine and remote health technologies contributes to environmental sustainability by reducing the need for patient travel, thereby lowering transport-related carbon emissions significantly (Purohit et al., 2021). Therefore, as seen in Fig. 3, lean practices and Healthcare 5.0 technologies will be the key drivers for economic, operational, and environmental efficiencies in the healthcare sector.

4.3 Limitations

Even though our results offer a good perspective on the lean thinking implementation of Healthcare 5.0 technologies, our results are only derived from the qualitative approach. This can bring bias and subjectivity to the current study. Our justification matrix is also limited to only 5 evaluation metrics. Furthermore, our results are only derived from the knowledge of authors and should include multiple expert information to increase the level of objectivity and also decrease the level of bias in the results.

5. Conclusions and Future Work

In this work, we have investigated the potential impacts of Healthcare 5.0 technologies on *Lean Thinking*. Our study first identified the level of justification categories, including relevance to lean principle, technology capabilities, implementation impact, innovative approach, and cross-industry insights with Healthcare 5.0 technologies. Then, we evaluated each of the Healthcare 5.0 technologies with a series of Lean principles including VSM, Kaizen, SMED, 5S, Heijunka, Jidohka, CI, JIT, Pull Flow, Waste Elimination, Kanban, Poka-Yoke, and Standardization. Our results show that AI will be the core Healthcare 5.0 technology for the integration of Lean principles in healthcare services. Robotics and DT technologies will be other integral parts of Lean implementations. IoMT, Blockchain, 6G, and Cloud/Edge Computing will serve as support systems for AI, Robotics, and DT in implementing Lean strategies. AM reduces the variability in production, which is an important factor for supporting Lean practices, this technology's usage can be limited in the healthcare industry. Furthermore, nanotechnology offers an innovative platform for wearable devices, but the current state of the technology does not offer as much importance as other Healthcare 5.0 technologies.

In the future, we plan to implement a more sophisticated lean assessment including both quantitative and qualitative approaches to assess the feasibility of the integration of lean principles into Healthcare 5.0 technologies. Our research efforts will also include a survey-based approach where the healthcare experts will evaluate the level of applicability of each Healthcare 5.0 technology based on our sophisticated lean assessment tool. Additionally, quantum computing technology may be included in Healthcare 5.0 technologies in future research efforts. This study can also be extended to Industry 5.0 technologies targeting more manufacturing applications rather than the healthcare focus. In other words, we are going to add a quantitative evaluation perspective along with our qualitative approach to create a more comprehensive assessment tool to offer less bias and more efficient results.

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Biographies

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Dr. Sinan Onal is a Chair/Associate Professor in the Department of Industrial Engineering and serves as the Director of the NSF-funded Motion Capture and Analysis Laboratory. His research lies in the broad areas of medical image processing, medical product development, machine learning & data mining, computational biomechanics, and engineering education. With over 12 years of industry experience, Dr. Onal has contributed to more than 20 scientific publications across various journals. He actively reviews for over 10 journals, and NSF proposals, and serves on several editorial boards, such as the Journal of Biomedical Graphics and Computing. Recognized for his contributions to research and teaching, he has received NSF funding, and the FY2020-2022 Hoppe Research Professor Award, and was honored with the 2017 Industrial Engineering Outstanding Teacher Award. He has enhanced the IE curriculum through the Undergraduate Research and Creative Activities Program and online course development. Invited by the National Academy of Engineering in 2015, he also advises the SIUE Chapter of the Institute of Industrial and System Engineers and directs the IISE Data Analytics & Information Systems Division, earning him the 2016 School of Engineering Outstanding Service Award.