

Smart Last-Mile Delivery in Healthcare: The Role of AI, Drones, and Autonomous Vehicles

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ABSTRACT

The last mile of healthcare logistics represents one of the most complex, costly, and critical segments of the healthcare supply chain. It directly influences the accessibility, timeliness, and reliability of essential medical supplies such as vaccines, blood products, pharmaceuticals, and diagnostic tools. Recent advances in artificial intelligence (AI), unmanned aerial vehicles (drones), and autonomous ground vehicles have significantly transformed this domain, enabling real-time decision-making, enhanced delivery efficiency, and improved healthcare outcomes. This literature review synthesizes current research on smart last-mile delivery systems in healthcare, focusing on the integration of AI-driven optimization, drone-enabled delivery, and autonomous vehicle technologies. It examines operational benefits, system architectures, challenges, and future directions, while highlighting the implications for global health equity and emergency preparedness.

Keywords: Smart logistics, healthcare supply chain, last-mile delivery, artificial intelligence, drones, autonomous vehicles, medical logistics, digital health, IoT

INTRODUCTION

The last mile of healthcare delivery represents the most sensitive and complex segment of the healthcare supply chain, where logistics directly intersect with patient outcomes [1-3]. Unlike conventional delivery systems, healthcare logistics must accommodate strict requirements for timeliness, temperature control, and product integrity. Delays in this stage can lead to severe consequences, including treatment interruptions, vaccine spoilage, and preventable mortality. As healthcare systems increasingly shift toward patient-centered care, the importance of efficient last-mile delivery has become even more pronounced [4, 5]. In many healthcare systems, last-mile delivery is disproportionately expensive and operationally challenging [6, 7]. Research has shown that this segment can account for more than half of total logistics costs due to fragmented demand, geographic dispersion, and infrastructure limitations [8-10]. These challenges are further amplified in rural and underserved areas where road networks are inadequate, and healthcare facilities are sparsely distributed. As a result, traditional logistics models often fail to meet the growing demand for timely and equitable healthcare access.

The emergence of digital technologies, particularly artificial intelligence, has begun to transform last-mile delivery from a reactive process into a proactive and predictive system [11, 12]. AI enables healthcare providers to anticipate demand patterns, optimize delivery routes, and respond dynamically to disruptions [13-15]. This transition marks a shift from static logistics planning to adaptive, real-time decision-making systems that can significantly enhance operational efficiency. Simultaneously, advancements in mobility technologies, such as drones and autonomous vehicles, have introduced new possibilities for overcoming physical and infrastructural barriers [16, 17]. These technologies offer innovative solutions for delivering medical supplies in hard-to-reach areas, reducing reliance on traditional transportation networks. Their integration into healthcare logistics has demonstrated significant potential in improving delivery speed and reliability. The convergence of AI, drones, and autonomous systems has given rise to the concept of smart last-mile delivery [18-20]. This paradigm emphasizes automation, connectivity, and intelligence, enabling healthcare systems to operate more efficiently and resiliently. This review aims to critically examine the role of these technologies in reshaping healthcare logistics and to identify the opportunities and challenges associated with their adoption.

CONCEPTUAL FOUNDATIONS OF SMART LAST-MILE HEALTHCARE DELIVERY

Smart last-mile delivery systems are built on the integration of digital intelligence and physical logistics infrastructure [21, 22]. At the core of these systems is the ability to collect, process, and act on real-time data. This data-driven approach allows healthcare providers to optimize delivery operations and ensure that medical supplies reach their destinations efficiently and safely. The shift toward data-centric logistics represents a fundamental transformation in how healthcare supply chains are managed. One of the key components of smart delivery systems is the use of interconnected technologies, particularly the Internet of Things (IoT) [23, 24]. IoT devices, such as sensors and tracking systems, provide continuous monitoring of critical parameters, including temperature, humidity, and location [25-27]. This real-time visibility ensures compliance with stringent healthcare standards, especially for temperature-sensitive products like vaccines and biologics.

Another foundational element is the concept of system interoperability. Smart delivery systems rely on seamless communication between various components, including warehouses, transportation units, and healthcare facilities [28-30]. This integration enables coordinated decision-making and reduces inefficiencies associated with fragmented logistics networks. Interoperability also facilitates the sharing of data across stakeholders, enhancing transparency and accountability. The adoption of hybrid delivery models further strengthens the conceptual framework of smart logistics [31, 32]. These models combine traditional transportation methods with emerging technologies such as drones and autonomous vehicles.

By leveraging the strengths of each mode of delivery, hybrid systems can achieve greater efficiency and flexibility. For example, trucks can transport bulk supplies to regional hubs, while drones handle the final delivery to remote locations [33]. Ultimately, smart last-mile delivery systems are characterized by their adaptability and resilience [34]. They are designed to respond to dynamic conditions, such as sudden changes in demand or disruptions caused by natural disasters. This capability is particularly important in healthcare, where timely delivery can mean the difference between life and death. As such, the conceptual foundations of these systems are closely aligned with the broader goals of improving healthcare accessibility and quality.

ARTIFICIAL INTELLIGENCE IN HEALTHCARE LAST-MILE DELIVERY

Artificial intelligence serves as the backbone of modern smart logistics systems, providing the computational power needed to analyze complex datasets and optimize delivery operations [35, 36]. In healthcare, AI applications extend beyond simple automation to include advanced decision-support systems that enhance both efficiency and reliability [37, 38]. These systems are capable of processing vast amounts of data from multiple sources, enabling more informed and timely decision-making. One of the most significant contributions of AI is in predictive analytics [39, 40]. By analyzing historical data and identifying patterns, AI models can forecast demand for medical supplies with remarkable accuracy [41]. This capability allows healthcare providers to allocate resources more effectively and avoid shortages or overstocking. Predictive analytics is particularly valuable during public health emergencies, where demand patterns can change rapidly and unpredictably.

AI also plays a critical role in route optimization. Traditional routing methods often rely on static planning, which fails to account for real-time variables such as traffic congestion or weather conditions [42]. In contrast, AI-driven algorithms can dynamically adjust delivery routes based on current data, ensuring that supplies reach their destinations as quickly as possible [43]. This not only reduces delivery times but also minimizes operational costs. Another important application of AI is in anomaly detection and quality assurance. Machine learning models can identify deviations from expected conditions, such as temperature fluctuations or delays in delivery [44, 45]. By detecting these anomalies early, healthcare providers can take corrective actions to prevent product spoilage or service disruptions. This is particularly important for maintaining the integrity of sensitive medical products. Finally, AI facilitates the integration and coordination of autonomous delivery systems [46, 47]. It enables efficient fleet management by optimizing dispatch schedules, energy usage, and maintenance requirements. Through advanced algorithms, AI ensures that drones and autonomous vehicles

operate in a synchronized and efficient manner. This level of coordination is essential for maximizing the benefits of smart delivery systems.

DRONE TECHNOLOGY IN HEALTHCARE LAST-MILE DELIVERY

Drone technology has emerged as a transformative force in healthcare logistics, particularly in addressing the challenges of last-mile delivery [48-50]. These unmanned aerial vehicles offer a unique advantage in their ability to bypass traditional transportation constraints, such as traffic congestion and poor road infrastructure. As a result, drones have become an effective solution for delivering medical supplies in remote and underserved areas. One of the primary benefits of drone delivery is speed. In emergency situations, such as the need for blood transfusions or critical medications, time is of the essence. Drones can significantly reduce delivery times by taking direct flight paths, avoiding delays associated with ground transportation [51, 52]. This capability has been shown to improve patient outcomes, particularly in life-threatening situations. Drones are also highly effective in reaching geographically isolated regions. In many parts of the world, healthcare facilities are located in areas that are difficult to access by road. Drones can overcome these barriers by providing direct aerial delivery, ensuring that essential supplies reach even the most remote communities. This has important implications for improving healthcare equity and access.

In addition to their operational advantages, drones offer cost benefits in certain contexts. While the initial investment in drone technology can be high, the long-term operational costs are often lower than those of traditional delivery systems [53-55]. This is particularly true in areas with limited infrastructure, where maintaining road networks can be expensive and challenging. Despite these advantages, drone technology faces several challenges, these include limitations in battery life, payload capacity, and susceptibility to weather conditions [56-60]. Regulatory barriers also pose significant obstacles, as airspace management and safety concerns must be addressed. Overcoming these challenges will be critical for the widespread adoption of drone delivery systems in healthcare.

AUTONOMOUS VEHICLES AND ROBOTICS IN HEALTHCARE DELIVERY

Autonomous vehicles represent another key innovation in smart last-mile delivery systems. These vehicles use advanced sensors, navigation systems, and artificial intelligence to operate without human intervention. In healthcare logistics, autonomous vehicles have the potential to significantly enhance efficiency and reduce reliance on human labor [61-63]. One of the main advantages of autonomous vehicles is their ability to operate continuously without fatigue. This allows for more consistent and reliable delivery schedules, particularly in urban environments where demand is high. By reducing the need for human drivers, these systems can also lower labor costs and improve overall operational efficiency.

Delivery robots, a subset of autonomous systems, are particularly useful for short-distance deliveries [64, 65]. These robots are commonly used in controlled environments, such as hospital campuses and university settings. Equipped with sensors and cameras, they can navigate sidewalks and indoor spaces, delivering supplies directly to patients or healthcare providers. The integration of autonomous vehicles with other delivery systems has led to the development of hybrid models [66, 67]. For example, trucks can transport goods over long distances, while autonomous robots handle the final delivery segment. This combination allows for greater flexibility and efficiency, particularly in complex logistics networks. However, the adoption of autonomous vehicles is not without challenges, these include technological limitations, such as navigation in complex environments, as well as regulatory and safety concerns. Public acceptance is also a critical factor, as trust in autonomous systems is essential for their widespread use. Addressing these challenges will be key to unlocking the full potential of autonomous delivery technologies.

INTEGRATION OF AI, DRONES, AND AUTONOMOUS VEHICLES

The integration of AI, drones, and autonomous vehicles represents the next frontier in healthcare logistics. These technologies, when combined, create a cohesive system capable of addressing the complexities of last-mile delivery. AI serves as the central intelligence layer, coordinating the activities of drones and autonomous vehicles to ensure efficient and reliable operations [68, 69]. One of the key benefits of integration

is the ability to optimize resource allocation [70]. AI algorithms can determine the most efficient combination of delivery methods based on factors such as distance, urgency, and environmental conditions. This ensures that each delivery is handled in the most effective manner, reducing costs and improving service quality.

Integrated systems also enhance resilience by providing multiple delivery options. In the event of a disruption, such as a road closure or adverse weather conditions, the system can quickly adapt by switching to an alternative delivery method [71-73]. This flexibility is particularly important in healthcare, where delays can have serious consequences. Another advantage of integration is improved scalability. By coordinating multiple delivery systems, healthcare providers can handle larger volumes of deliveries without compromising efficiency. This is especially important during periods of high demand, such as pandemics or natural disasters. Despite these benefits, integration poses significant challenges, including system complexity and the need for robust infrastructure. Ensuring seamless communication between different components requires advanced technological solutions and significant investment. However, the potential benefits of integrated systems make them a promising area for future research and development.

IMPLICATIONS FOR GLOBAL HEALTH AND EQUITY

Smart last-mile delivery technologies have the potential to significantly improve global health outcomes by increasing access to essential medical services. In many low- and middle-income countries, healthcare access is limited by geographical and infrastructural barriers [74, 75]. Technologies such as drones and autonomous vehicles can help bridge these gaps, delivering medical supplies to remote and underserved communities. The use of AI further enhances equity by enabling more efficient allocation of resources. By analyzing data on population health and demand patterns, AI systems can prioritize deliveries to areas with the greatest need. This ensures that limited resources are used effectively, improving overall healthcare outcomes.

In addition to improving access, smart delivery systems can enhance the resilience of healthcare systems [76, 77]. During emergencies, such as disease outbreaks or natural disasters, these technologies can ensure the rapid delivery of critical supplies. However, the adoption of these technologies must be approached carefully to avoid exacerbating existing inequalities. For example, regions with limited digital infrastructure may be unable to fully benefit from smart delivery systems [78]. Addressing these disparities will be critical for ensuring that the benefits of these technologies are distributed equitably. Ultimately, smart last-mile delivery systems have the potential to transform healthcare delivery on a global scale. By improving access, efficiency, and resilience, these technologies can contribute to better health outcomes and reduced disparities. Continued investment and research will be essential to realize this potential.

CHALLENGES AND RESEARCH GAPS

Despite the promising advancements in smart last-mile delivery, several challenges remain that hinder widespread adoption. One of the most significant barriers is the regulatory environment. The deployment of drones and autonomous vehicles is subject to strict regulations, particularly concerning safety and airspace management. Navigating these regulatory frameworks can be complex and time-consuming. Technological limitations also pose significant challenges. Issues such as limited battery life, payload capacity, and system reliability can restrict the effectiveness of these technologies. While ongoing research is addressing these limitations, further advancements are needed to enable large-scale deployment.

Infrastructure requirements represent another major obstacle. Smart delivery systems rely on robust digital infrastructure, including high-speed connectivity and data integration platforms. In many regions, particularly in low-resource settings, this infrastructure is lacking, limiting the feasibility of implementation. Ethical and social concerns must also be considered. Issues related to data privacy, security, and public acceptance can impact the adoption of these technologies. Ensuring that systems are transparent and secure will be critical for building trust among users and stakeholders. Finally, there is a need for more real-world implementation studies. While many theoretical models and pilot projects demonstrate the potential of smart delivery systems, large-scale deployments remain limited. Future research should focus on evaluating the performance of these systems in real-world settings to better understand their impact and scalability.

FUTURE DIRECTIONS

Future research in smart last-mile delivery should focus on developing scalable and sustainable solutions. This includes the design of hybrid delivery models that integrate multiple technologies to optimize performance. Such models have the potential to significantly enhance efficiency and reduce costs. Advancements in artificial intelligence will play a critical role in shaping the future of healthcare logistics. Emerging techniques, such as reinforcement learning and edge computing, can further improve decision-making and system responsiveness. These technologies enable real-time optimization and reduce reliance on centralized systems. Energy efficiency and sustainability are also important areas of focus. As the use of drones and autonomous vehicles increases, it is essential to minimize their environmental impact. Research into alternative energy sources and more efficient battery technologies will be critical in this regard. The development of supportive regulatory frameworks will be essential for enabling innovation. Policymakers must work closely with industry stakeholders to create regulations that ensure safety while encouraging technological advancement. This includes addressing issues related to airspace management and data governance. Finally, expanding real-world pilot programs will be crucial for validating the effectiveness of smart delivery systems. These programs provide valuable insights into operational challenges and help refine system designs. By scaling successful pilots, healthcare providers can accelerate the adoption of these technologies and realize their full potential.

CONCLUSION

Smart last-mile delivery represents a transformative advancement in healthcare logistics, driven by the integration of artificial intelligence, drones, and autonomous vehicles. These technologies have the potential to address longstanding challenges in healthcare delivery, particularly in terms of efficiency, accessibility, and reliability. The adoption of these systems enables healthcare providers to move from reactive to proactive logistics models. By leveraging real-time data and advanced analytics, smart delivery systems can anticipate demand, optimize operations, and respond effectively to disruptions. This results in improved service quality and better patient outcomes. Drones and autonomous vehicles further enhance these capabilities by providing innovative solutions for overcoming physical and infrastructural barriers. Their ability to operate in challenging environments makes them particularly valuable for delivering medical supplies in remote and underserved areas. However, realizing the full potential of these technologies requires addressing significant challenges, including regulatory barriers, technological limitations, and ethical concerns. Continued research and collaboration will be essential for overcoming these obstacles and ensuring sustainable adoption. In conclusion, smart last-mile delivery systems hold immense promise for transforming healthcare logistics. By improving efficiency, resilience, and equity, these technologies can contribute to a more effective and inclusive healthcare system.

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