Global Social Sciences Bulletin (GSSB)
Yıl / Year: **2025**, Cilt / Volume: **2**, Sayı / Issue: **2**, ss / pp: **207-215**

Last-Mile Logistics in Smart Cities: Digital Technologies and Innovative Solutions[1]

Akıllı Şehirlerde Son Kilometre Lojistiği: Dijital Teknolojiler ve Yenilikçi Çözümler

Makale Başvuru Tarihi: 12.11.2025
Makale Kabul Tarihi: 28.12.2025
Makale Türü: Araştırma Makalesi

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Anahtar Kelimeler:

Akıllı Şehirler,

Son Kilometre Lojistiği,

IoT,

Yapay Zekâ,

Dijital Teslimat Sistemleri,

ÖZET

Bu çalışma, akıllı şehirlerde giderek karmaşıklaşan son kilometre lojistiğinin dijital teknolojiler aracılığıyla nasıl dönüştürüldüğünü incelemektedir. E-ticaret hacmindeki hızlı artış ve kentleşmenin yol açtığı yoğun talep, şehir içi dağıtım süreçlerini daha maliyetli, çevresel açıdan yükleyici ve operasyonel açıdan daha kırılgan hâle getirmiştir. Bu bağlamda, IoT tabanlı izleme ve görünürlük sistemleri, yapay zekâ destekli rota optimizasyonu ve talep tahmini ile dijital teslimat platformları ve akıllı teslimat dolapları gibi yenilikçi uygulamaların son kilometre performansına katkıları literatür temelli bir derleme yaklaşımıyla değerlendirilmiştir. Bulgular, IoT altyapılarının gerçek zamanlı izleme ve koordinasyonu geliştirdiğini, yapay zekâ tabanlı algoritmaların rota planlama verimliliğini artırdığını ve dijital teslimat sistemlerinin yeniden teslimat oranlarını ve trafik yoğunluğunu azalttığını göstermektedir. Bununla birlikte, veri bütünlüğü ve güvenliği, operasyonel uyumsuzluklar, düzenleyici belirsizlikler, altyapı gereksinimleri ve toplumsal kabul gibi sınırlılıkların dijital çözümlerin yaygınlaşmasını zorlaştırdığı görülmektedir. Sonuç olarak çalışma, akıllı şehirlerde sürdürülebilir ve dirençli lojistik sistemlerinin oluşturulması için bütünleşik veri altyapılarına, çok paydaşlı yönetişim modellerine ve hibrit teslimat yaklaşımlarına yönelik araştırmaların önemini vurgulamaktadır.

Keywords:

Smart Cities,

Last-Mile Logistics,

Digital Technologies,

IoT,

Artificial Intelligence,

ABSTRACT

This study examines how digital technologies are transforming the increasingly complex last-mile logistics in smart cities. The rapid increase in e-commerce volume and the intense demand driven by urbanization have made urban distribution processes more costly, environmentally burdensome, and operationally fragile. In this context, a literature-based review approach was used to evaluate the contributions of innovative applications such as IoT-based tracking and visibility systems, AI-powered route optimization and demand forecasting, digital delivery platforms, and smart delivery lockers to last-mile performance. The findings demonstrate that IoT infrastructures improve real-time monitoring and coordination, AI-based algorithms increase route planning efficiency, and digital delivery systems reduce redelivery rates and traffic congestion. However, limitations such as data integrity and security, operational incompatibilities, regulatory uncertainties, infrastructure requirements, and social acceptance hinder the widespread adoption of digital solutions. In conclusion, the study highlights the importance of research on integrated data infrastructures, multi-stakeholder governance models and hybrid delivery approaches for the creation of sustainable and resilient logistics systems in smart cities.

Önerilen Alıntı (Suggested Citation): ASADOLLAHI, Vahideh, EBADOLLAHIKALKHORAN, Mohsen, GÜROL, Pınar (2025), "*Last-Mile Logistics in Smart Cities: Digital Technologies and Innovative Solutions*", **Global Social Sciences Bulletin**, S.2(2), ss.207-215.

1 This publication is based on the master's thesis of Vahideh Asadollahi, completed in the Logistics Management Program at the Graduate School of Istanbul Ticaret University.

1. INTRODUCTION

During the last decades, cities worldwide have grown in both physical size and population, and it is foreseen that more than 70% of the global population will live in cities by 2050 (World Bank, 2024). This demographic and spatial change has increased the demand for sustainable, efficient, and technology-supported urban management systems. In this framework, the Smart City concept has resulted from the interaction between sustainability goals and digital technologies, enhancing the integration of technological innovation with social and human capital for improving the quality of urban life (Cardoso de Oliveira et al., 2024). Although Smart Cities are characterized by data-driven infrastructures that support mobility, energy consumption, public services, and environmental monitoring, the rapid growth of global e-commerce has put special pressure on the distribution networks of cities. Last-mile logistics has therefore become a core issue of transportation planning, environmental sustainability strategies, and service quality policies in contemporary cities.

However, last-mile logistics in Smart Cities also entails a number of operational and structural challenges, notably due to dense traffic networks, fragmented delivery routes, and the increasing frequency of small-sized and individualized shipments. Such challenges raise significant demands for logistics systems that will be not only efficient but also flexible and adaptive to real-time conditions within the urban environment. The role of digital technologies is very important in this respect, enabling dynamic route optimization, enhancing supply chain visibility, and alternative forms of delivery that meet urban-specific needs. Knowing how such technologies are integrated into the urban last mile is, therefore, crucial for developing sustainable and resilient urban freight systems.

In this study, the role of digital technologies in responding to the challenges of last-mile logistics within Smart Cities is emphasized. It discusses how IoT-based monitoring systems, AI-based route optimization, and innovative delivery modes contribute to more efficient, sustainable, and resilient urban distribution processes. As a review study, this research employs a secondary data analysis approach, drawing on academic literature and digital sources to synthesize existing knowledge in the field. The objective of the study is to synthesize current approaches and practices to achieve a comprehensive understanding of technology-driven last-mile logistics solutions in the contemporary urban environment.

2. CONCEPTUAL BACKGROUND

2.1. Smart Cities and Digital Urban Infrastructure

The concept of the smart city has evolved in response to increasing complexity in urban contexts and the need for more efficient, sustainable, and resilient systems. In a way, smart city approaches represent integrated ways to combine social, economic, and environmental objectives by using information and communication technologies, placing human capital and citizen well-being at their core (Albino et al., 2015). Therefore, smart cities are interconnected urban ecosystems where continuous learning through data-driven processes and digital tools enhance decision-making and the offering of public services in support of economic competitiveness. At the core of a smart city lies the digital urban infrastructure, which provides the technological basis for data capture, transport, storage, and analysis. Typically, the infrastructure includes sensor networks, broadband communication systems, cloud computing environments, and data platforms that enable real-time monitoring and service integration across city domains (Marchesani et al., 2023). Digital infrastructure will support the development of digital public services as it forms the information architecture necessary to deliver services that are adaptive, effective, and user-oriented (Kumar et al., 2020). In this respect, information and communication technologies and data networks act as enabling mechanisms in enhancing the efficiency and sustainability of urban operations. For instance, integrating a wide variety of public services, such as mobility, transportation, utilities, and environmental monitoring, calls for broadband networks and cloud-based systems that allow timely information exchange between public and private actors (Anthopoulos, 2017; Wirtz et al., 2019).

Information and communication technologies driven control and monitoring frameworks enable cities to monitor and manage services in real time, achieving better use of resources and improving public safety (Wolniak et al., 2024). However, the implementation of a digital infrastructure also gives rise to new aspects of governance, security, and social equity. Digital ecosystems are complex and thus often require coordination among several stakeholders-public authorities, private providers of technology, and citizens (Praharaj et al., 2018; Viale Pereira et al., 2017). Furthermore, cities need to address issues with data privacy, interoperability of digital systems, and long-term infrastructure maintenance costs. This creates a situation of inequality in digital service access, a challenge that might lead to restrictions in citizen participation and a threat to the principle of inclusion (Wu et al., 2018; Braun et al., 2018).

In summary, the foundation of smart cities rests on integrated digital infrastructures that allow for data-driven governance while supporting innovative service models. However, besides technological capacity, the overall success of such systems is tied to effective institutional coordination, citizen engagement, and appropriate sustainable investment strategies. Hence, smart city development necessarily involves the integration of technological innovation with broader socio-economic and environmental priorities as drivers for truly livable and inclusive urban environments.

2.2. Urban Logistics and the Last-Mile Problem

Urban logistics refers to the flow of goods within the urban environment, which is directly affected by population density, commercial activity, and spatial constraints. The last mile is generally considered the costliest, intensive, and polluting part of the supply chain: the final stage of delivery from a local distribution point to the final customer. According to relevant literature, last-mile activities can take up 13–75% of the total logistics costs due to the individualized nature of deliveries, route fragmentation, and time-sensitive fulfillment pressures (Silva et al., 2023).

From an environmental point of view, the last mile is highly responsible for urban congestion, air pollution, and noise, since road-based freight transport dominates city centers (Bosona, 2020). Increasing demand for e-commerce amplifies these trends, yielding more frequent deliveries and lower shipment volumes that commonly produce "empty trip" patterns and poor vehicle utilization. These inefficiencies reflect not only energy and emission burdens but also broader urban sustainability challenges related to public health, street safety, and livability (Viu-Roig and Alvarez-Palau, 2020).

The spatial form of the city affects the complexity of last-mile logistics. The characteristics of densely and historically rich urban centers have narrow streets, pedestrian priority zones, and inadequately allocated areas for either parking or loading; this therefore brings operational constraints that extend delivery times and result in more routing irregularities (Silva et al., 2023). Moreover, delivery failures, such as the absence of the recipient, lead to repeated deliveries, which has negative consequences for operational cost and environmental impact as well (Yılmaz et al., 2022).

At the same time, consumer expectations are changing. The increase of e-commerce has been paralleled by demands for quicker, more flexible, and more individual solutions to delivery. Simulation-based analyses illustrate that consumer preferences also change over time and impact market viability of alternative last-mile delivery models, and there will be no single successful delivery configuration because of the challenges to balance cost, reliability, and convenience under changing conditions (Van Vliet et al., 2025).

These challenges outline a need for innovative, technology-supported last-mile strategies that will enhance routing efficiency, consolidate deliveries, reduce vehicle kilometers traveled, and curb congestion and emissions. Approaches that rethink distribution areas beyond the narrow "last mile" model, such as coordinated multi-city or "last 50 miles" systems, have also been discussed as ways to improve sustainability outcomes (Faccio and Gamberi, 2015).

3. DIGITAL TECHNOLOGIES IN LAST-MILE LOGISTICS

Increasingly complex last-mile logistics in cities have raised awareness of the need for data-driven, technology-supported delivery systems. Digital technologies enhance visibility, efficiency, and responsiveness across last-mile distribution processes through continuous data collection, real-time communication, adaptive routing, and contactless delivery solutions. IoT-based tracking infrastructures improve operational transparency and coordination, while AI-powered optimization mechanisms enable predictive and dynamic decision-making in routing and demand management. At the same time, alternative digital delivery platforms and parcel locker networks provide alternative delivery configurations that reduce failed deliveries, alleviate congestion, and enhance consumer convenience. All these technological systems put together form an integral digital framework that strengthens the sustainability and resilience of last-mile logistics within smart cities.

3.1. IoT-Based Tracking and Visibility Systems

IoT-based tracking and visibility systems lie at the heart of attempts to enhance efficiency and visibility in last-mile logistics. IoT infrastructures enable incessant data exchange between delivery vehicles, warehouses, and control centers for real-time monitoring and coordination across logistics networks. These systems are based on integrated sensors, GPS modules, and communication interfaces to acquire and transfer relevant data of operational interest, such as location, status of parcels, environmental conditions, and traffic (Sorooshian et al., 2022).

This flow of real-time information enhances operational visibility, thus providing logistical managers with an early look at disruptions to adjust the schedule of deliveries. The systems of IoT-enabled visibility also contribute to dynamic routing and adaptive decision-making. Driven by integrated sensor networks and cloud-based data platforms, logistics operators can evaluate current traffic density, delivery urgency, and resource availability in order to adjust routes in real time (Ieva et al., 2025).

IoT technologies further support autonomous and semi-autonomous delivery modes, including delivery robots and drone-assisted last-mile operations. Smart, IoT-connected robot vehicles can collect, share, and analyze operational data to optimize delivery tasks, communicate with control centers, and respond to contextual changes such as road congestion or weather variations (Sujatha et al., 2024).

Overall, IoT-based tracking and visibility systems form the digital backbone of technology-driven last-mile logistics. They enhance transparency across supply chain actors, enable flexible and adaptive routing strategies, and serve as a necessary foundation for emerging autonomous delivery solutions. The functional and strategic value of IoT in last-mile operations underlines its core enabling technology role in smart city logistics infrastructures.

3.2. AI-Based Route Optimization and Demand Forecasting

The difficulty of last-mile delivery operations is determined by factors such as the density of urban traffic flow, time-variable delivery demand, and boundaries imposed on energy use. Within this framework, AI-based route optimization enables real-time data stream analysis and dynamic route adjustments. The AI algorithms consider parameters like road traffic congestion, weather conditions, and frequency of deliveries to minimize travel time and decrease operational costs. Route optimization applications have been found capable of yielding significant gains in delivery efficiency and cost reduction in various studies (Ferreira and Esperança, 2025).

A core contribution of AI-supported systems is dynamic routing, which enables continuous route adjustments based on real-time conditions instead of relying on pre-determined routing patterns. In particular, genetic algorithms and machine learning–based models have been shown to optimize the sequencing of delivery stops, minimizing total distance traveled and service time. Integrating weather data and traffic prediction models into route planning further enhances operational flexibility in dense urban environments, where even minor disruptions can escalate delivery delays (Horchuk et al., 2024).

Demand forecasting is another critical application area of AI in last-mile logistics. AI-driven forecasting models use historical demand data in conjunction with external variables such as seasonality, social trends, and economic indicators to predict surges in delivery volumes. This enables more effective planning related to fleet capacity, warehouse replenishment, and delivery scheduling. Current research points out that integrated data analytics and deep learning–based forecasting bring significant enhancement in the forecast accuracy of demand and help towards agile urban delivery operations (Yarlagadda, 2025).

Meanwhile, in support of developing distributed and flexible delivery networks, the increasing adoption of AI-based optimization strategies is also observed. AI systems enhance delivery continuity and widen the operational reach when integrated with micro-fulfilment centers, urban consolidation hubs, and autonomous delivery solutions. Furthermore, emerging evidence suggests that with combinations like autonomous vehicles, electric delivery fleets, and AI-based routing, improvements in energy efficiency and emission reductions as high as 15-40% could be achieved (Ferreira and Esperança, 2025).

Overall, AI-driven route optimization and demand forecasting act as strategic levers that enhance both environmental sustainability and service performance in last-mile logistics. Automation of processes and extension of decision-support capabilities make the logistics networks more efficient, adaptive, and customeroriented. However, the high costs of initial investments and the need for robust data integration systems are still some of the main considerations for large-scale implementation (Shuaibu et al., 2025).

3.3. Digital Delivery Platforms and Parcel Locker Networks

Digital delivery platforms and parcel locker networks have emerged as key elements in the sustainable last-mile logistics of smart cities. These systems apply automation, connectivity, and shared digital infrastructures toward higher service flexibility with a reduction in delivery costs, traffic congestion, and environmental externalities. Automated parcel lockers, specifically, are noted for their potential to consolidate deliveries and reduce failed delivery attempts-major drivers of inefficiency in door-to-door logistics (Deutsch and Golany, 2018).

Smart parcel locker systems are designed to allow customers to collect or return parcels with digital access codes or mobile applications, and the operation is often integrated with e-commerce and logistics platforms. They act as unmanned collection and delivery points, which are located in residential areas, shopping centers, and mobility hubs, placed in such a position to encourage access modes without using combustion engines (Knapskog et al., 2025). Compared to home delivery, parcel lockers lower vehicle kilometers traveled, reduce operational costs, and support decarbonization objectives in urban freight transport (Schnieder et al., 2021).

Recent research emphasizes the integration of parcel lockers with other delivery models, including staffed collection and delivery points and autonomous systems. Combining lockers with staffed pickup points increases utilization and service reliability, while investment costs are kept more in check, particularly under fluctuating demand conditions (Schnieder et al., 2021).

This is further supported by the evolving nature of parcel-locker sharing models, showing an increased involvement of digital collaboration among logistics service providers. Pang et al., (2024) proposed a locker-sharing framework where asset-owning firms rent the unused locker capacity to non-asset operators, thereby attaining higher utilization and profitability with a reduction in redundant vehicle trips. This cooperative approach reflects the transition from isolated logistics operations to platform-based ecosystems reliant on real-time data exchange and dynamic allocation of urban space.

Governance and policy perspectives are equally important in sustaining these digital delivery infrastructures. Vakulenko, (2023) noted that the growth of parcel lockers requires clear regulatory frameworks and coordination between municipalities, logistics companies, and property owners in a way that balances commercial interests with the management of public space. On their part, Knapskog et al., (2025) emphasized that multi-level governance networks may lead the deployment of lockers toward the objectives of equitable accessibility, emission reduction, and urban livability. Generally, such platforms for digital delivery and networks of parcel lockers are setting the pace toward data-driven, user-centric logistics ecosystems that are sustainable. These systems enhance the resilience and efficiency of last-mile delivery within smart cities through IoT connectivity, integrated routing algorithms, and smart urban planning.

4. CHALLENGES AND LIMITATIONS

Despite the transformative potential of digital technologies and innovative delivery models, last-mile logistics in smart cities continues to face substantial constraints. The literature underlines that current solutions are embedded in complex operational environments characterized by fragmented flows, volatile demand, and multiple stakeholders with partly conflicting objectives (Na et al., 2022). These conditions generate technological, organizational, regulatory, and socio-environmental challenges.

4.1. Technological and Data-Related Constraints

The integration of IoT, AI, and autonomous systems into last-mile logistics requires robust digital infrastructures and high-quality data. However, still problems continuing with data fragmentation, lack of interoperability, and uncertain data governance across logistics networks (Na et al., 2022 ; Agnusdei et al., 2022).

AI-powered and intelligent last-mile technologies also face technical barriers related to reliability, safety, and cyber-security. Sorooshian et al., (2022) emphasize that both tangible technologies (robots, drones, autonomous vehicles) and intangible tools (optimization algorithms, decision-support platforms) are vulnerable to system failures, cyber-attacks, and sensor inaccuracies.

Unmanned aerial vehicle delivery systems illustrate the tension between technological promise and implementation limits. While mobile-edge computing and blockchain architectures can enhance low-latency navigation and secure transaction recording, unmanned aerial vehicles remain constrained by limited payload capacity, short battery life, and stringent operational requirements (Li et al., 2020).

Furthermore, Industry 4.0 technologies in last- mile logistics demand substantial upfront investments in sensors, communication networks, and analytics capabilities, while their economic benefits are not always straightforward to quantify.

4.2. Operational and Business Model Limitations

From an operational perspective, last-mile logistics continues to be the least efficient and most costly part of the supply chain, even when digital technologies are deployed. Reviews of urban freight highlight persistent issues such as fragmented deliveries, low vehicle load factors, empty running, and short route lengths, all of which undermine cost efficiency (Bosona, 2020 ; Na et al., 2022).

Risk analyses of e-commerce last-mile operations underscore that technology alone does not eliminate core vulnerabilities. Raj et al., (2024) identify lack of visibility, low efficiency, and unpredictable elements as major “hidden risk hurdles,” with critical criteria including insufficient real-time tracking, unstable GPS performance, and fluctuating demand patterns. These findings suggest that without robust process redesign, digital tools may simply shift or further expose existing operational risks.

New business models associated with shared infrastructure and multi-actor networks are also difficult to implement. Coordinating reverse flows to support circular economy strategies requires synchronized planning and aligned incentives among retailers, logistics service providers, and technology vendors (Agnusdei et al., 2022).

4.3. Sustainability, Governance, and Social Acceptance Issues

Although many technology-driven solutions aim to improve environmental performance, their net sustainability effects are not always straightforward. Zhu et al., (2023) argue that new transportation modes may shift environmental impacts rather than eliminate them. For example, through increased electricity demand, new forms of visual and noise pollution, or the material footprint of additional infrastructure such as parcel lockers and robot docking stations.

Regulatory and governance frameworks have not fully caught up with the speed of technological development. Drone-based and autonomous vehicle delivery are subject to strict safety, liability, and air-space regulations, while data-intensive systems face evolving requirements in privacy and cyber-security (Li et al., 2020 ; Sorooshian et al., 2022). Moreover, governance of multi-actor last-mile systems is complicated by the need to reconcile commercial interests of logistics providers with public objectives in congestion management, emissions reduction, and urban livability (Bosona, 2020).

Social acceptance and labour-market implications constitute another layer of limitation. Sorooshian et al., (2022) point out that AI-enabled last-mile technologies raise concerns about job displacement, surveillance, and fairness in human–machine interaction, which may provoke resistance from workers, unions, and local communities. In addition, digital delivery channels can exacerbate inequalities in access to services when certain groups lack the necessary digital skills or connectivity.

5. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The rapid digital transition of urban logistics is transforming the shape and operation of last-mile delivery within a smart city. As the review findings illustrate, the integration of IoT-based visibility systems, AI-driven optimization tools, and digital delivery platforms offers unparalleled opportunities for improving operational efficiency, service quality, and environmental sustainability in urban freight distribution. These technologies enable real-time monitoring, predictive decision-making, adaptive routing, and new forms of delivery that collectively enhance the resilience and responsiveness of last-mile networks. Simultaneously, parcel locker systems and platform-based delivery ecosystems present promising strategies through which flows are consolidated, failed deliveries reduced, and congestion in densely populated urban areas can be eased.

Despite these developments, the review also shows that last-mile logistics remains one of the most complicated and constrained elements of the urban supply chain. Data fragmentation, interoperability issues, and infrastructural shortcomings continue to make technological integration an uphill struggle. Advanced systems become prone to operational inefficiencies: low load factors, fragmented delivery flows, and shifting demand levels. The introduction of emerging technologies like drones, autonomous delivery vehicles, and robot-assisted distribution adds even more concerns over regulatory adequacy, cyber-security, environmental side effects, and social acceptance. These issues call for holistic governance frameworks and multi-actor coordination mechanisms that align technological innovation with greater sustainability and equity goals in smart cities.

In the light of perspectives outlined in this study, several research directions appear for each of the technological, operational, and socio-environmental challenges. One important area concerns the development of integrated digital infrastructures to ensure secure, interoperable, high-quality data flows across logistics actors. Future studies can be devoted to the architecture of unified data-sharing platforms, standardized communication protocols, and AI governance mechanisms to enable fair, transparent, and reliable decision-making. Another relevant research avenue involves considering hybrid last-mile models that incorporate autonomous delivery, micro-fulfilment centers, and parcel locker networks, especially for various urban densities and differing consumer behaviors. Simulation-based and real-world pilot studies could provide valuable insights into the optimal configuration of these multimodal systems.

YAZAR BEYANI / AUTHORS' DECLARATION:

Bu makale Araştırma ve Yayın Etiğine uygundur. Beyan edilecek herhangi bir çıkar çatışması yoktur. Araştırmanın ortaya konulmasında herhangi bir mali destek alınmamıştır. Makale yazım ve intihal/benzerlik açısından kontrol edilmiştir. Makale, "*en az iki dış hakem*" ve "*çift taraflı körleme*" yöntemi ile değerlendirilmiştir. Yazar(lar), dergiye imzalı "*Telif Devir Formu*" belgesi göndermişlerdir. Mevcut çalışma için mevzuat gereği etik izni alınmaya ihtiyaç yoktur. Bu konuda yazarlar tarafından dergiye "*Etik İznine Gerek Olmadığına Dair Beyan Formu*" gönderilmiştir. / This paper complies with Research and Publication Ethics, has no conflict of interest to declare, and has received no financial support. The article has been checked for spelling and plagiarism/similarity. The article was evaluated by "*at least two external referees*" and "*double blinding*" method. The author(s) sent a signed "*Copyright Transfer Form*" to the journal. There is no need to obtain ethical permission for the current study as per the legislation. The "*Declaration Form Regarding No Ethics Permission Required*" was sent to the journal by the authors on this subject.

YAZAR KATKILARI / AUTHORS' CONTRIBUTIONS:

Kavramsallaştırma, orijinal taslak yazma, düzenleme – **Y1,Y2** ve **Y3**, veri toplama, metodoloji, resmi analiz – **Y1, Y2** ve **Y3**, Nihai Onay ve Sorumluluk – **Y1, Y2** ve **Y3**. / Conceptualization, writing-original draft, editing – **Y1, Y2** and **Y3**, data collection, methodology, formal analysis – **Y1, Y2** and **Y3**, Final Approval and Accountability – **Y1, Y2** and **Y3**.

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