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Model-Driven Engineering for Smart Cities: A Systematic Literature Review of Techniques, Challenges, and Emerging Trends

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Abstract: Model-Driven Engineering (MDE) has become a key approach for addressing the complexity and heterogeneity of smart city systems. However, the state-of-the-art in MDE applications for smart cities remains underexplored. This study systematically reviews 42 primary studies, published between January 2019 and August 2024, to examine how MDE techniques are applied in smart cities, focusing on tools, techniques, and challenges. Six key themes emerged: MDE tools and techniques, security and privacy, scalability and interoperability, digital twins and emerging technologies, strategic alignment and enterprise architecture, and testing and verification. These themes highlight MDE's potential to enable high-level design, rapid prototyping, and integration of diverse technologies. While tools like SI4IoT and InterSCity demonstrate MDE's adaptability, challenges such as scalability, real-world validation, and lack of standardization persist. This study provides a comprehensive understanding of the state-of-the-art, identifies emerging trends, and proposes future research directions to address existing gaps, paving the way for more robust and scalable MDE solutions in smart cities.

Keywords: Model-Driven Engineering; Smart Cities; Systematic Literature Review; Scalability and Interoperability; IoT Integration.

1. INTRODUCTION

Smart cities represent a transformative vision for urban development, leveraging advanced technologies such as Internet of Things (IoT) networks, Artificial Intelligence (AI), and data analytics to enhance sustainability, efficiency, and quality of life [1, 2]. These systems integrate interconnected devices and infrastructure, ranging from smart grids and autonomous transportation to intelligent waste management and real-time public safety monitoring, to optimize resource allocation, reduce environmental impact, and enhance citizen services. For example, smart traffic systems use real-time data from sensors and cameras to alleviate congestion, while energy management platforms dynamically balance supply and demand across urban grids [3]. However, the inherent complexity and heterogeneity of smart city ecosystems pose significant challenges [4, 5]. Such systems must seamlessly integrate diverse technologies (e.g., sensors, actuators, edge-fog-cloud architectures) while ensuring interoperability across proprietary platforms, scaling to accommodate growing urban populations, and maintaining real-time responsiveness for critical applications like emergency response and healthcare.

Model-Driven Engineering (MDE) has emerged as a promising approach to address these challenges by promoting the utilization of models as first-class entities in the development process. MDE aims to automate the process from the design stage to the implementation stage, raising the abstraction level from computational notions to a level more understandable to developers and stakeholders [6]. A model, in this context, is an abstract representation of a system that eliminates unnecessary details to increase users' understanding of the system under consideration [7]. Furthermore, a metamodel describes the structure of a modelling language, defining its abstract syntax [8]. Transformations, such as model-to-model (M2M) and model-to-text (M2T), play a critical role in converting models into other models or text (e.g., source code) [9].

MDE has been applied in various smart city scenarios to address specific challenges. For instance, the SI4IoT methodology is proposed in [10], which employs Domain Specific Languages (DSLs) and model-to-text transformations to integrate heterogeneous IoT systems across platforms like Arduino and Node-Red. In the context of urban mobility, a model-driven framework for integrating smart traffic fog nodes and homes is developed [11]. These examples demonstrate the versatility of MDE in addressing diverse smart city challenges, from IoT integration to urban planning and real-time decision-making. However, despite these advancements, the application of MDE in smart cities remains fragmented, with limited synthesis of its benefits, limitations, and best practices.

The literature on many aspects of MDE and smart cities has been independently examined using various systematic approaches. For instance, research on smart cities has been reported in studies like [12] and [13], while research on the application of MDE from various angles has been reviewed by [14] and [15]. Our study, on the other hand, investigates the literature on the applicability of MDE in the context of smart cities. To the best of our knowledge, no such work has been published previously. Hence, there is a need to investigate the constantly expanding body of knowledge of applying MDE tools and techniques to cope with the challenges of designing and developing smart city systems.

By identifying significant correspondence between the results obtained from the evaluation of the new research questions, this study provides a structured overview of the field. Such an overview is invaluable for both industry researchers and practitioners, as it helps determine the challenges and opportunities of MDE applications in smart cities. Without such a study, determining what has been suggested, completed successfully, or failed would remain a challenging task. We have systematically reviewed 42 primary studies (identified out of 223) published between January 2019 and August 2024. Our analysis identifies six key themes highlighting the transformative role of MDE in enabling rapid prototyping, integrating heterogeneous systems, and embedding security considerations into design workflows. However, challenges such as limited real-world validation, lack of standardization in deployments (i.e., edge, fog, or cloud), and gaps in socio-technical alignment persist.

The remainder of the paper is structured as follows. Section 2 introduces the systematic review protocol adopted in this study. In Section 3, we present the results of the review. Section 4 provides an in-depth analysis of the results along with the validity threats. Section 5 presents future research directions, and Section 6 describes a summary of the related works. Finally, Section 7 concludes the paper.

2. METHODOLOGY

The goal of a systematic literature review (SLR) is to evaluate and analyse the body of knowledge about a particular topic. This review of the literature on MDE for smart cities is performed following the protocol outlined by Kitchenham [16]. The rest of this section describes the activities performed for planning, conducting, and reporting the review.

2.1 Research Questions

The main goal of this SLR is to identify the MDE techniques used for smart cities, the benefits of using MDE, and the particular challenges encountered in doing so. The following research questions are formulated to achieve this goal.

- **RQ1:** What MDE techniques have been used for smart cities?
- **RQ2:** What are the potential advantages of using MDE techniques to address smart city challenges?
- **RQ3:** What are the challenges of adopting MDE techniques for smart cities?

The population in this study is the intersection of the domains of MDE and smart cities. Research studies published in peer-reviewed journals, conferences, and book chapters from January 2019 to August 2024 are considered. Figure 1 depicts the research methodology used to identify primary studies. The rest of this section provides descriptions of the phases of the study protocol. The results of the study are covered in Section 3.

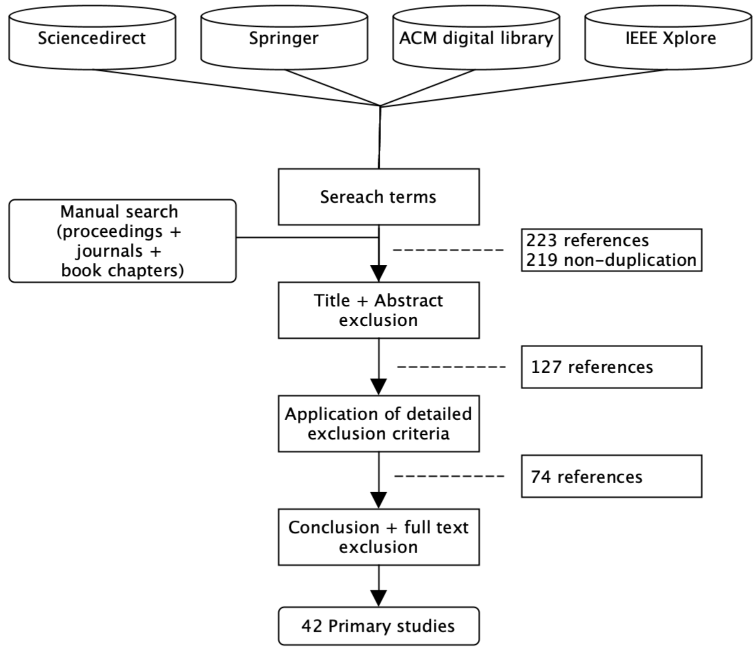

Fig. 1: Multi-step filtering of studies and final number of primary studies.

2.2 Search Strategy and Data Sources

We searched four scientific databases, including the Sciencedirect, ACM Digital Library, IEEE Xplore Digital Library, and SpringerLink, to find relevant articles for our systematic review. The search strategy was formulated after conducting a pilot search using different combinations of the terms "model-driven engineering", "MDE", "smart city", and "smart cities". The search was restricted to title, abstract, and keywords. Also, other terms such as "urban" and "intelligent" were used, but they gave us unrelated papers on smart cities. Table 1 presents the exact strings used in each database along with the frequency of the retrieved papers.

Table 1: Search strings used with papers retrieved from different research databases.

Source	Search string	Papers
Science Direct	("Smart City" AND "Model-Driven Engineering") OR ("Smart City" AND "MDE") OR ("Smart Cities" AND "Model-Driven Engineering") OR ("Smart Cities" AND "MDE")	95
Springer	"Smart City "AND "Model-Driven Engineering" OR "Smart City" AND "MDE" OR "Smart Cities" AND "Model-Driven Engineering" OR "Smart Cities" AND "MDE"	59
ACM Digital Library	Smart City AND Model-Driven Engineering OR Smart City AND MDE OR Smart Cities AND Model-Driven Engineering OR Smart Cities AND MDE	38
IEEE Xplore	Smart City AND Model-Driven Engineering OR Smart City AND MDE OR Smart Cities AND Model-Driven Engineering OR Smart Cities AND MDE	31

2.3 Inclusion and Exclusion of Articles

Establishing exclusion and inclusion criteria is a crucial phase in the research selection procedure. A study was excluded if it:

1. is not written in the English language
2. does not have full text available online
3. does not present an application of MDE techniques for smart cities
4. represents academic theses
5. is a book review

We include all studies that address aspects of MDE and its relationship to the smart city. The study selection was done in multiple steps (see Figure 1):

3. In the initial stage of the research selection process, we reviewed the abstracts and titles of 223 publications, discarding those unrelated to MDE and smart cities. The specified exclusion criteria were applied to categorize each paper as relevant, non-related, or unclear. This stage concluded with 4 duplicated studies, 20 relevant documents, 92 unrelated, and 127 unclear studies.
4. The second step involved examining the unclear studies in full to assess their relevance to MDE applications in the smart city domain. For each paper, we began by reviewing the introduction and conclusion sections, and then examined other sections as needed for decision-making. This full-text review resulted in 74 papers identified as relevant.
5. The last step of study selection was to read the full text of the 94 papers. We had a total of 42 primary studies for our SLR.

3. RESULTS

This section synthesizes findings from 42 primary studies (ScienceDirect: 12, ACM: 7, Springer: 7, IEEE: 16) organized into six themes that emerged through a gradual process of grouping related ideas that consistently appeared across the reviewed studies. For example, discussions around model-based threat detection, privacy-preserving mechanisms, and access control often overlapped, prompting us to integrate them under a broader "Security and Privacy" theme. Similarly, various works on system reliability, simulation, and verification techniques were brought together into the "Testing and Verification" theme. Rather than being pre-defined, these themes took shape through ongoing analysis, cross-referencing, and refinement until clear clusters emerged.

Figure 2 depicts the cumulative increase in relevant and included publications from January 2019 onward. It is important to note that trends cover the first 8 months of the year 2024. The incomplete data for 2024 can be linearly projected forward to cover the entire 2024 year. The forecasted trends in retrieved and included publications for 2024 are more accurate and comparable to those from 2019 to 2023.

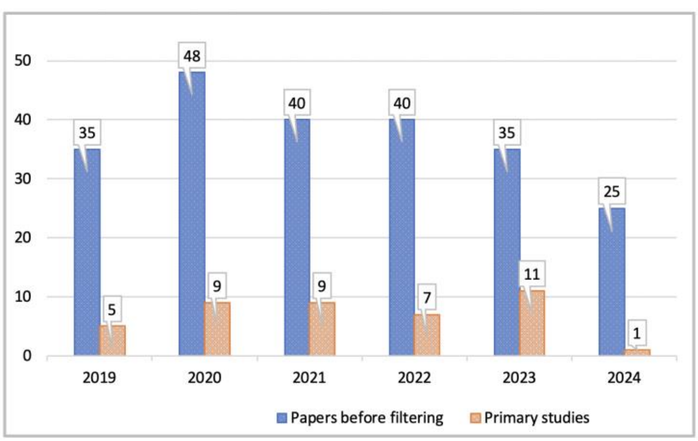

Fig. 2: Relevant and included papers by years.

3.3 Tools and Techniques

Model-Driven Engineering (MDE) tools are pivotal in addressing smart city challenges through domain-specific abstractions and automation, as highlighted in a review of the application of emerging technologies in [17]. The SI4IoT methodology proposed in [10] employs a domain-specific language (DSL) and model-to-text transformations to integrate heterogeneous IoT systems across platforms like Arduino and Node-Red, validated through performance tests using Gatling. InterSCity, introduced in [18], was an open-source microservices platform designed for scalable smart city applications, tested via large-scale simulations with OpenStreetMap and Sim-Diasca. Industrial IoT (IIoT) interoperability is handled in [19] by proposing a Model-Driven Architecture (MDA) framework, which reduces development effort for heterogeneous devices, demonstrated through a smart city case study. A study reported in [20] simplifies IoT application development with AutoIoT, a user-driven framework that generates server-side code from JSON models, evaluated through an experiment involving 54 developers. Despite these advancements, tools FaultFlow, detailed in [21], which automates failure analysis through SysML-to-STPN transformations, reveal limitations in scalability testing, as seen in its Pollution Monitor System case study. The MIKADO framework in [22] addresses KPI assessment challenges using metamodel-based DSLs, validated through a demonstration case and scalability studies. Research reported in [23] introduces an MDE framework for Web of Things (WoT), enabling protocol interoperability and application heterogeneity, validated through an LED control case study on an ESP8266 IoT device. An integrated architecture combining MD-DSM and smart city platforms to facilitate application development across domains is proposed in [24]. A DSL for FIWARE-based IoT simulations, validated through case studies in smart building and agricultural IoT environments, is provided in [25]. Table 2 presents the MDE tools along with their types and applications in the domain of smart cities.

Table 2: MDE tools and applications.

Tool	Type	Application	Papers
SI4IoT	DSL	IoT Integration	[10]
InterSCity	Microservices	Scalable Platforms	[18]
AutoIoT	Code Generator	IoT Applications	[20]
FaultFlow	SysML/STPN	Failure Analysis	[21]
WoT Framework	Node-WET, WebSockets	Web of Things	[23]
MD-DSM	Integrated Architecture Development	App Development	[24]
FIWARE	IoT Simulations	Agricultural IoT Environments	[25]
MIKADO	DSL	KPI Assessment	[22]
MDA Framework	IIoT	Reduce Development Effort	[19]

3.4 Security and Privacy

Several studies, like [26], discussed that security and privacy solutions in smart cities emphasize model-based analysis and user-centric consent management. Research presented in [27] proposes SoSSecML, a modelling language for secure Systems-of-Systems (SoS), combined with Multi-Agent Systems (MAS) to predict cascading attacks in smart buildings, validated through a case study of Adelaide University's energy systems during peak consumption hours. The "privacy paradox" in IoT with the Informed Consent Management Engine (ICME), addressed [28], which provides fine-grained visibility into data collection practices, was tested via a Node-RED implementation and interviews with 15 industry experts. Formalization of safety and security verification for IoT applications using rewriting logic (Maude) is presented in [29], transforming ThingML specifications into analyzable models, as demonstrated in the PingPong IoT case study. While [30] systematically reviews 803 studies on model-based security testing in IoT, highlighting gaps in empirical validation, [21] presents a FaultFlow tool that automates failure analysis for IoT systems through SysML-to-STPN transformations, tested on a Pollution Monitor System. These approaches predominantly rely on simulations and case studies, with limited integration into broader MDE workflows. MDA is used in [31] to ensure Role-Based Access Control (RBAC) in IoT devices, validated through a smart door lock case study, which grants or denies access based on sensor inputs. Figure 3 depicts the distribution of the validation methods used in studies discussing the security and privacy aspects of MDE in the domain of smart cities.

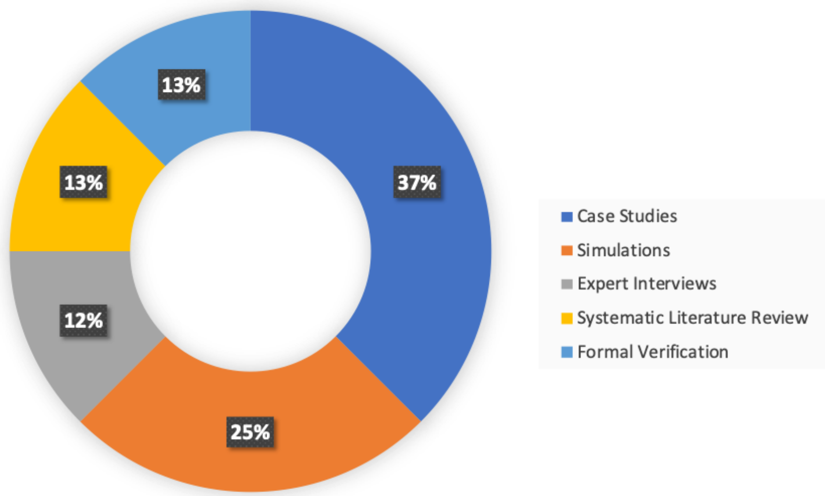

Fig. 3: Distribution of validation methods in security studies.

3.5 Scalability and Interoperability

Scalability and interoperability solutions focus on distributed architectures and semantic integration. InterSCity platform leverages microservices and simulations (OpenStreetMap, InterSCSimulator) to validate scalability for smart city applications [18]. A model-based fleet deployment framework for the IoT-edge-cloud continuum, tested in collaboration with a smart healthcare provider to automate software orchestration across edge gateways, is proposed in [18]. A study reported in [11] integrates smart traffic fog nodes and homes using a model-driven approach, validated through a real-world case study. Meanwhile, [33] systematically reviews existing Fog modelling languages to identify gaps in standardization and interoperability for edge-fog-cloud systems. Optimization of Quality of Service (QoS) in vehicular fog computing (VFC) through dynamic resource provisioning, using a multi-objective optimization model to balance latency and resource utilization, is presented in [34]. Semantic interoperability is addressed in [35] through knowledge base overlays **to** unify heterogeneous IoT data streams, and in [36] via the Distributed Data Interoperability Layer (DDIL) for smart grids. Despite progress, standardization remains a challenge, particularly for edge-fog-cloud deployments. Table 3 presents the proposed MDE-based scalability solutions along with validation methods in the domain of smart cities.

Table 3: Scalability and interoperability.

Solution/Aspect	Validation Method	Papers
InterSCity	OpenStreetMap Simulations	[18]
Fleet Deployment	DevOps Experiments	[32]
Traffic Fog Integration	Real-World Case Study	[11]
Fog modelling languages and QoS		[33,34]
Semantic interoperability		[35]
DDIL	Smart grids	[36]

3.6 Digital Twins and Emerging Technologies

Digital Twins (DTs) and 3D modelling are increasingly applied for predictive analytics and system resilience. In [37], authors propose an Urban Intelligence, a modular DT framework which combines multidisciplinary city models (infrastructure, user behaviour) with numerical optimization, targeting urban planning challenges. Enhancement of cyber-physical system resilience through the integration of digital twins with failure models, as validated in smart city and industrial IoT scenarios, is discussed in [38]. In contrast, [39] analyzes the transition from 3D modelling to DTs in smart manufacturing and transportation, highlighting limitations in real-time synchronization and applicability across domains. "Digital Dice", introduced in [39], is a W3C-compliant virtual representation of IoT devices using microservices, demonstrated in a smart building case study. While these frameworks show promise in predictive maintenance (e.g., [38]) and urban planning (e.g., [37]), adoption in domains like waste management remains limited. A framework for synchronizing is introduced [41], city spatial models with graph-based analyzable models, enabling safe model-driven development of composite systems in physical spaces. Synchronization is enabled in [42] between CityGML models and analysable models, ensuring consistency in physical space modelling for composite systems. Figure 4 depicts the distribution of the DT applications by domains.

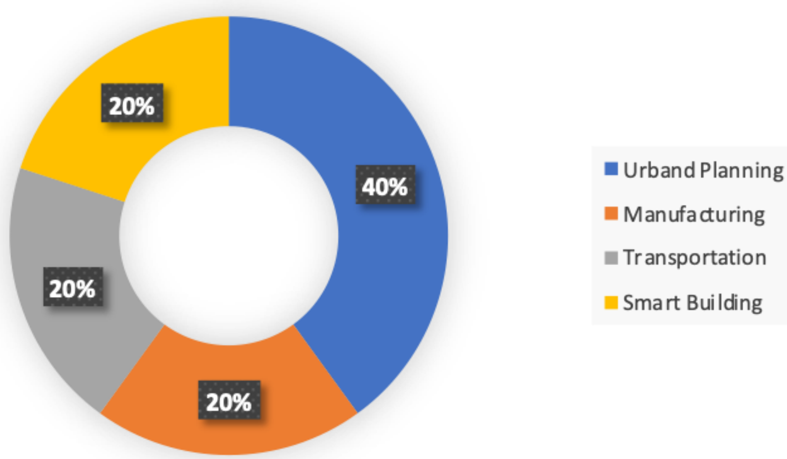

Fig. 4: Digital twin applications by domain.

3.7 Strategic Alignment and Enterprise Architecture

Strategic alignment bridges technical implementations with city management goals through standardized frameworks and KPIs. Design principles for Smart City Enterprise Architectures (SCEA) are derived from a review of the literature and validated through case studies of two cities [43]. ICT criteria, as incorporated in [44], were used in smart city rankings through a Multiple-Attribute Decision Making (MADM) approach, tested on New York, Seoul, and Santander. A study reported in [45] automates dashboard development with Cities-Board, transforming KPI lists into interactive visualizations for urban data. In [67], authors explore model-driven optimization for 6G network planning, although limited to single-objective functions. These efforts highlight the need for domain-specific KPIs (e.g., MADM in [44]) and automated governance tools (e.g., Cities-Board in [45]) to align technical deployments with strategic objectives. A model-driven approach, as outlined in [46], offers a technology-agnostic solution for transforming KPIs into interactive dashboards, thereby reducing manual effort and errors in dashboard setup. Real-time IoT applications for connected vehicles are targeted in [47], utilizing communication protocols such as Wi-Fi, Bluetooth, and 5G to enhance the Quality of Experience (QoE). Table 4 presents strategic alignment approaches along with their use cases proposed in the domain of smart cities.

Table 4: Strategic alignment approaches.

Approach	Use Case	Papers
SCEA Design Principles	Enterprise Architecture	[43]
MADM Rankings	ICT Evaluation	[44]
Cities-Board	Dashboard Automation	[45]
KPI-based Interactive Boards	Dashboard Automation	[46]
Communication Protocol	Connected Vehicles	[47, 76]

3.8 Testing and Verification

Testing and verification ensure system reliability through formal methods and empirical validation. In [48], authors analysed 803 studies on Robotic and Autonomous Systems, identifying temporal logic and state machines as widely used modelling approaches, and highlighting gaps in industrial applicability. Research work discussed in [29] formalizes the semantics of ThingML using rewriting logic (Maude), enabling automated verification of IoT applications, as demonstrated in the PingPong distributed services case study. STAS for runtime generation of component-based applications, proposed in [49] and validated through mashup user interfaces, demonstrating the importance of dynamic testing in MDE. A hardware-in-the-loop (HIL) testbed for edge-based cyber-physical systems, simulating environmental scenarios to evaluate dependability in smart city mobility, is developed [50]. In [51], the presented approach ensures functional correctness in WoT applications through model checking, extending the Mozilla WebThings platform. A CI/CD metamodel to standardize IoT architectures is highlighted in [52], though empirical validation remains limited. While simulations dominate validation (e.g., [18]), tools FaultFlow [21] demonstrate the potential of automated failure analysis, albeit with scalability constraints. “Ref. [53]” proposes MLM to streamline the development of QESs, demonstrating its applicability through running examples. Figure 5 depicts the distribution of the verification methods in testing studies, with simulations as the most widely used verification method.

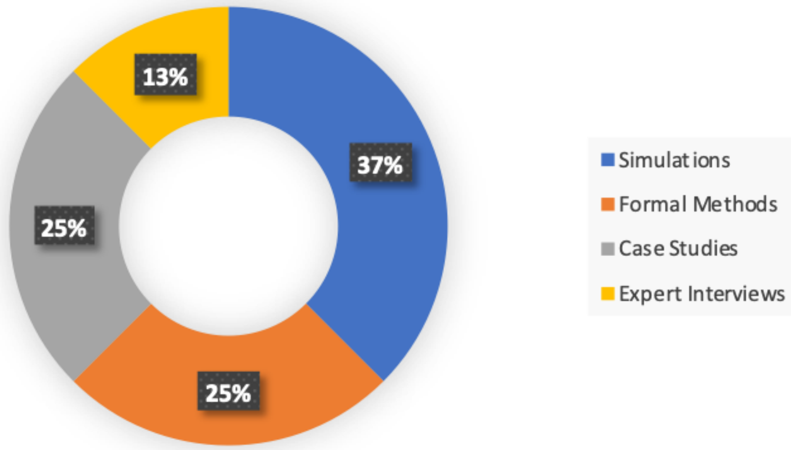

Fig. 5: Verification methods in testing studies.

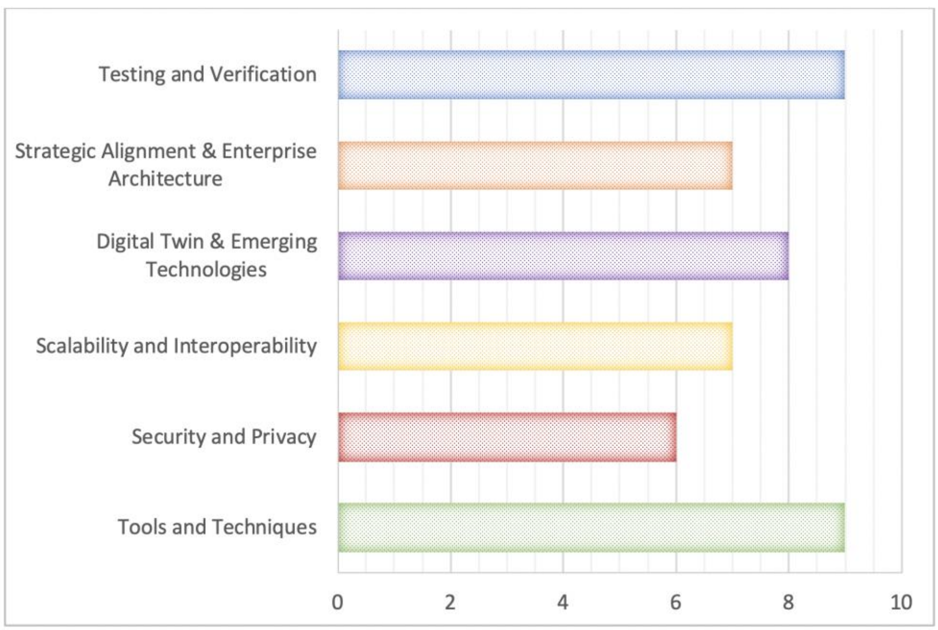

Fig. 6: Number of publications focused on the six identified themes.

4. DISCUSSION

The findings from the 42 primary studies reveal a complex and evolving landscape of MDE applications in smart city development. As shown in Figure 6, the dominant themes in the MDE for smart cities relate to the use of Tools and Techniques and Testing and Verification. The application of MDE to Security and Privacy aspects is the least explored area. Some of the studies, like [18], can be related to several themes, hence are counted accordingly. This section synthesizes the results, critically analyzes their implications, and provides a forward-looking perspective on the role of MDE in addressing the multifaceted challenges of smart cities.

4.1 Synthesis of Findings

The six themes identified in Section 3 highlight both the transformative potential and the persistent challenges of applying MDE in the domain of smart cities.

Tools and Techniques: The growing use of DSLs and model-to-text transformations, as seen in tools like SI4IoT and AutoIoT, demonstrates the adaptability of MDE in addressing the heterogeneity and complexity of smart city systems. These tools allow developers to abstract away low-level implementation details, enabling a stronger focus on high-level design and faster prototyping. However, scalability remains a critical issue. For example, while InterSCity shows promising performance in large-scale simulations, its real-world effectiveness across diverse urban settings—each with unique infrastructural, socio-economic, and regulatory challenges—has not yet been thoroughly evaluated. This gap emphasizes the need for tools that are not only technically robust but also capable of adapting to varying contextual demands.

Security, Privacy, Scalability, and Interoperability: The increasing reliance on IoT devices in smart cities has amplified concerns around data security and user privacy. Model-based approaches like SoSSecML and ICME offer innovative solutions by embedding security and privacy considerations into the design phase. However, these approaches often rely on simulations or limited case studies, raising questions about their scalability and effectiveness in real-world deployments. For instance, while ICME provides fine-grained visibility into data collection practices, its reliance on expert interviews for validation limits its generalizability. Moreover, the dynamic nature of cyber threats necessitates continuous updates to these models, which is often overlooked in current implementations. The distributed nature of smart city systems necessitates scalable and interoperable solutions. Frameworks like InterSCity and DDIL address these challenges through distributed architectures and semantic integration. However, the lack of standardization, particularly in edge-fog-cloud deployments, remains a significant barrier. For example, while [33] identifies gaps in Fog modelling languages, there is a pressing need for standardized frameworks that can seamlessly integrate edge, fog, and cloud resources. This lack of standardization not only hampers interoperability but also increases the complexity of system integration and maintenance.

Digital Twins and Emerging Technologies: DTs represent a paradigm shift in how smart city systems are designed, monitored, and optimized. Frameworks like Urban Intelligence and Digital Dice demonstrate the potential of DTs in urban planning and smart building management. However, their adoption in other domains, such as waste management and transportation, is still limited. Additionally, real-time synchronization across heterogeneous systems remains a challenge, as highlighted by [39]. This limitation is particularly critical in applications requiring real-time decision-making, such as traffic management and emergency response.

Strategic Alignment and Enterprise Architecture: Aligning technical implementations with city management goals is crucial for the success of smart city projects. Frameworks like SCEA and tools like Cities-Board provide valuable insights into this alignment. However, the development of domain-specific KPIs and automated governance tools is still in its early stages. For instance, while [44] incorporates ICT criteria into smart city rankings, there is a need for more comprehensive frameworks that can evaluate the socio-economic impact of smart city initiatives. This gap underscores the importance of developing metrics that capture not only technical performance but also social equity, environmental sustainability, and economic viability.

Testing and Verification: Ensuring the reliability of smart city systems through rigorous testing and verification is essential. Formal methods, such as rewriting logic and model checking, are widely used for this purpose. However, the reliance on simulations for validation, as seen in [18] and [50], limits the generalizability of these methods. Tools like

FaultFlow demonstrate the potential for automated failure analysis, but their scalability in large-scale deployments remains unproven. This limitation highlights the need for more robust testing frameworks that can handle the complexity and scale of real-world smart city systems.

4.2 Addressing Research Questions

The findings provide clear answers to the research questions posed in this study:

RQ1: What MDE techniques have been used for smart cities? MDE techniques applied in smart cities include DSLs, model-to-text transformations, and formal modelling approaches. Tools like SI4IoT and AutoIoT leverage DSLs to integrate heterogeneous IoT systems, while frameworks such as InterSCity use microservices for scalable smart city applications. Additionally, formal methods like rewriting logic and model checking are employed for system verification and validation. These techniques enable developers to abstract low-level implementation details, focus on high-level design, and accelerate prototyping. However, their adoption varies across domains, with some areas like urban planning and smart building management showing more progress than others, such as waste management and transportation.

RQ2: What are the potential advantages of using MDE techniques to address smart city challenges? MDE techniques offer several advantages in addressing smart city challenges. They enable the abstraction of complex system details, allowing developers to focus on high-level design and rapid prototyping. Tools like SI4IoT and InterSCity demonstrate how MDE can streamline the integration of heterogeneous IoT systems and improve scalability. Furthermore, MDE supports the embedding of security and privacy considerations into the design phase, as seen in frameworks like SoSSecML and ICME. By providing modular and hierarchical modelling capabilities, MDE techniques also facilitate the development of scalable and interoperable solutions that are critical for the distributed nature of smart city systems.

RQ3: What are the challenges of adopting MDE techniques for smart cities? Despite their advantages, adopting MDE techniques for smart cities presents several challenges. Scalability remains a significant issue, as many tools, such as InterSCity, perform well in simulations but lack real-world validation across diverse urban contexts. The lack of standardization, particularly in edge-fog-cloud deployments, hampers interoperability and increases system integration complexity. Security and privacy concerns are also prominent, especially in IoT deployments, where dynamic cyber threats require continuous model updates. Additionally, the reliance on simulations for validation, as seen in tools like SoSSecML and FaultFlow, limits the generalizability of these methods. Finally, integrating MDE with legacy systems and emerging technologies like 5G and blockchain remains a work in progress, highlighting the need for further research and development.

It is also important to highlight that our findings have significant implications for various stakeholders involved in smart city development. Researchers should focus on addressing the scalability and interoperability challenges of MDE tools and techniques. More empirical studies and real-world validations are needed to ensure the practical applicability of these tools. Additionally, exploring the integration of MDE with emerging technologies, such as 5G and blockchain, presents a promising avenue for future research. Practitioners can leverage existing MDE tools, such as SI4IoT and InterSCity, to streamline the development of smart city applications. However, they must be mindful of the scalability and interoperability limitations of these tools. Adopting standardized frameworks and governance tools can help align technical deployments with strategic city management goals. Policymakers should prioritize the development of standardized frameworks and governance tools to ensure the successful implementation of smart city projects. Investments in Digital Twins and predictive analytics can enhance urban planning and system resilience. Additionally, fostering collaboration between academia, industry, and government can accelerate the adoption of MDE in smart cities.

4.3 Validity Threats

There can be different threats to the validity of study results. First, while the research provides a comprehensive review of MDE techniques for smart cities, it is limited to studies published between January 2019 and August 2024. This timeframe, though extensive, may exclude earlier foundational works that could offer additional insights into the evolution of MDE in smart cities. As a result, the findings may not fully capture the historical development and long-term trends in the field.

Second, the scope of the literature review is primarily limited to peer-reviewed peer reviewed journals, conferences, and book chapters, which may exclude valuable insights from industry reports, grey literature, and practical case studies. This could introduce a bias toward academic perspectives, potentially overlooking practical challenges and solutions identified in real-world implementations.

Third, the analysis is restricted to studies published in English, potentially overlooking contributions from non-English-speaking regions. This may limit the generalizability of the findings, as smart city initiatives in non-English-speaking countries may face unique challenges and adopt different approaches.

Finally, the field of smart cities is rapidly evolving, with new tools, frameworks, and technologies emerging continuously. While this study captures developments up to August 2024, some findings may become outdated as the field progresses. These validity threats highlight the need for future research to broaden the temporal scope, include diverse linguistic and regional perspectives, and account for the fast-paced evolution of smart city technologies.

5. FUTURE RESEARCH DIRECTIONS

Based on the findings of this study, several critical areas for future research have been identified. These directions aim to address the existing gaps and challenges in the application of MDE to smart city development, while also exploring new opportunities for innovation and impact.

The lack of standardized frameworks for smart city applications is a significant barrier to scalability and interoperability. Future research should focus on developing standardized MDE frameworks that can be applied across diverse domains, such as transportation, energy, and healthcare. These frameworks should include unified modelling languages and metamodels that can capture the complexity of smart city systems, guidelines for integrating MDE with existing urban infrastructure and legacy systems, and best practices for ensuring compliance with regulatory and ethical standards, particularly in data-sensitive domains like healthcare and public safety. Standardization will not only enhance interoperability but also reduce the complexity of system integration and maintenance, making MDE more accessible to practitioners and policymakers.

DTs have shown immense potential in predictive analytics and system resilience, but challenges in real-time synchronization limit their adoption. Future research should explore advanced synchronization techniques that can handle the dynamic and heterogeneous nature of smart city systems. This includes integrating DTs with real-time data streams from IoT devices, edge computing nodes, and cloud platforms, as well as developing domain-specific DTs for applications like traffic management, waste collection, and emergency response, where real-time decision-making is critical. Enhancing real-time synchronization will enable DTs to provide actionable insights and support proactive decision-making in smart cities.

The integration of MDE with emerging technologies, such as 5G, edge computing, and blockchain, presents a promising avenue for addressing scalability and interoperability challenges. Future research should investigate the role of 5G networks in enabling low-latency communication and real-time data processing for MDE-based smart city applications. Additionally, the use of edge computing to decentralize data processing and reduce the load on cloud infrastructure, particularly in resource-constrained environments, should be explored. The application of blockchain for secure and transparent data sharing across smart city systems, ensuring data integrity and trust, is another area of interest. These technologies can enhance the performance, security, and scalability of MDE frameworks, enabling new use cases and applications in smart cities.

While simulations and case studies are valuable for validating MDE tools and techniques, there is a pressing need for more empirical studies and real-world deployments. Future research should focus on conducting large-scale pilot projects in real-world urban environments to evaluate the scalability and effectiveness of MDE frameworks. Collaborating with city governments, industry partners, and community stakeholders will ensure that MDE solutions are contextually relevant and socially inclusive. Developing benchmarking frameworks and performance metrics to assess the impact of MDE on key smart city outcomes, such as energy efficiency, traffic congestion, and public safety, will also be critical. Empirical validation will bridge the gap between theoretical research and practical deployment, ensuring that MDE solutions are robust, reliable, and impactful.

The alignment of technical implementations with city management goals requires the development of domain-specific Key Performance Indicators (KPIs). Future research should focus on creating KPIs that capture not only technical performance but also social equity, environmental sustainability, and economic viability. Automating the collection and analysis of KPI data using MDE tools and techniques will enable real-time monitoring and decision-making. Integrating KPIs into governance frameworks and policy-making processes will ensure that smart city initiatives are aligned with the needs and priorities of urban communities. Domain-specific KPIs will provide a holistic view of smart city performance, enabling stakeholders to make informed decisions and measure the impact of their investments.

Smart city development is not just a technical challenge but also a socio-technical one, involving complex interactions between technology, society, and governance. Future research should explore the social and ethical implications of MDE in smart cities, particularly in areas like data privacy, algorithmic bias, and digital inclusion. The role of participatory design and citizen engagement in shaping MDE frameworks and ensuring that they reflect the needs and values of urban communities should also be investigated. Additionally, the development of governance models that can balance innovation with accountability, ensuring that smart city initiatives are transparent, inclusive, and equitable, is a critical area for future work. Addressing socio-technical challenges will ensure that MDE solutions are not only technically sound but also socially responsible and ethically grounded.

Smart city systems are inherently interdisciplinary, requiring collaboration across domains like urban planning, computer science, environmental science, and social sciences. Future research should promote interdisciplinary research initiatives that bring together experts from diverse fields to address the complex challenges of smart city development. Collaborative platforms and tools that enable knowledge sharing and co-creation across domains will foster innovation and creativity. Training programs and capacity-building initiatives that equip researchers and practitioners with the skills and knowledge needed to work across disciplinary boundaries will also be essential. Cross-domain collaboration will enable a more holistic and integrated approach to smart city development, ensuring that MDE solutions are comprehensive and impactful.

6. RELATED WORK

Smart city development has been widely discussed, and several systematic literature reviews and mapping studies have explored tools and technologies related to smart cities, but they often focus on specific domains or challenges. For instance, [54] and [55] have explored software product line (SPL) engineering and privacy-compliant software development in IoT systems. These studies highlight challenges such as variability management and privacy compliance, but do not focus on the broader context of smart cities or the role of MDE in addressing these challenges. In the domain of DTs, studies like [56] and [57] have investigated architectural models, security, scalability, and interoperability, as well as the use of ontologies to address challenges in smart contracts. While these studies provide valuable insights into high-fidelity data modelling and real-time properties, they do not specifically address the role of MDE in smart cities. Similarly, [58] and [59] have conducted systematic mapping studies on security, privacy, and trust in systems-of-systems, as well as Big Data Management (BDM) mechanisms in IoT. Although these studies highlight challenges such as managing large-scale IoT data and ensuring privacy compliance, they do not focus on the broader application of MDE techniques in smart cities.

Similarly, the literature of MDE has also been reviewed from different perspectives. Research reported in [60] analysed 98 primary studies on the use of machine learning to solve MDE problems, and [61] examined 36 primary studies on the current state-of-the-art on MDE for model composition. In the context of Cyber-physical Systems (CPS), 140 studies published during 2010–2018 for identifying and classifying the MDE practices are analysed in [62], while [63] considered 29 primary studies to investigate the traceability management within MDE. Other related reviews, such as those described in [64] and [65], have explored formal and semi-formal methods for requirement engineering in industrial CPSs and modelling languages for cyber-physical production systems. While these studies provide valuable insights into the use of MDE techniques in complex systems, they do not specifically address the application of these techniques in smart cities. Similarly, research presented in [48] and [66] has examined testing interventions for robotics and autonomous systems and cloud-based modelling tools in the IoT domain. Although these studies are relevant to smart cities, they do not focus on the broader application of MDE techniques in this context.

While earlier research has explored MDE or smart cities independently, our study bridges these domains by focusing specifically on how MDE techniques are applied within smart city ecosystems. Unlike prior reviews, which often narrow their scope to individual technologies (e.g., IoT, robotics) or isolated challenges (e.g., privacy, scalability), our work dives deep into the interplay between MDE and smart cities, synthesizing insights from 42 primary studies to uncover how MDE tools and methodologies address real-world urban complexities. For instance, while tools like SI4IoT and InterSCity demonstrate MDE's adaptability in IoT integration and scalability, our analysis reveals gaps in standardization and real-world validation that earlier studies overlooked. By connecting these dots, we offer a big-picture view of MDE's role in smart cities—highlighting not just its potential but also the hurdles that demand attention. This dual focus on practical applications and systemic challenges sets our work apart, offering researchers and practitioners a roadmap to harness MDE more effectively in urban innovation.

7. CONCLUSIONS

This study systematically reviewed 42 primary studies, published between January 2019 and August 2024, to explore how Model-Driven Engineering (MDE) techniques are applied in smart cities. We identified six key themes: tools and techniques, security and privacy, scalability and interoperability, digital twins and emerging technologies, strategic alignment and enterprise architecture, and testing and verification. These themes highlight the potential of MDE to address the complexity and heterogeneity of smart city systems, enabling high-level design, rapid prototyping, and integration of diverse technologies. Tools like SI4IoT and InterSCity demonstrate how MDE can streamline IoT integration and improve scalability, while frameworks like SoSSecML and ICME embed security and privacy considerations into the design phase.

However, challenges remain. Scalability and real-world validation are critical issues, as many tools perform well in simulations but lack testing in diverse urban contexts. The lack of standardization, particularly in edge-fog-cloud deployments, hampers interoperability and increases system integration complexity. Additionally, integrating MDE with emerging technologies like digital twins, 5G, and blockchain requires addressing real-time synchronization and socio-technical challenges, such as data privacy and algorithmic bias.

Future research should focus on developing standardized MDE frameworks, enhancing real-time capabilities, and conducting empirical validations to bridge the gap between theory and practice. By addressing these gaps, MDE can play a pivotal role in creating sustainable, resilient, and inclusive smart cities.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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الهندسة الموجهة بالنماذج للمدن الذكية: مراجعة منهجية للأدبيات حول التقنيات والتحديات والاتجاهات الناشئة

الملخص: أصبحت الهندسة الموجهة بالنماذج نهجًا رئيسيًا لمعالجة تعقيد وتنوع أنظمة المدن الذكية. ومع ذلك، لا تزال أحدث التقنيات في تطبيقات الهندسة الموجهة بالنماذج للمدن الذكية غير مستكشفة. تستعرض هذه الدراسة بشكل منهجي 42 دراسة أولية نُشرت بين يناير 2019 وأغسطس 2024، لفحص كيفية تطبيق تقنيات الهندسة الموجهة بالنماذج في المدن الذكية، مع التركيز على الأدوات والتقنيات والتحديات. ظهرت ستة موضوعات رئيسية: أدوات وتقنيات الهندسة الموجهة بالنماذج، والأمان والخصوصية، وقابلية التوسع والتشغيل البيني، والتوائم الرقمية والتقنيات الناشئة، والمحاذاة الاستراتيجية وهندسة المؤسسة، والاختبار والتحقق. تسلط هذه المواضيع الضوء على إمكانات MDE لتمكين التصميم عالي المستوى والنمذجة السريعة ودمج التقنيات المتنوعة. وفي حين توضح أدوات مثل SI4IoT وInterSCity قدرة MDE على التكيف، إلا أن التحديات مثل قابلية التوسع والتحقق في العالم الحقيقي والافتقار إلى التوحيد القياسي لا تزال قائمة. توفر هذه الدراسة فهمًا شاملاً لأحدث التقنيات، وتحدد الاتجاهات الناشئة، وتقترح اتجاهات بحثية مستقبلية لمعالجة الفجوات الحالية، وتمهيد الطريق لحلول MDE أكثر قوة وقابلية للتوسع في المدن الذكية.

الكلمات المفتاحية: الهندسة القائمة على النماذج؛ المدن الذكية؛ مراجعة الأدبيات المنهجية؛ قابلية التوسع والتشغيل البيني؛ تكامل إنترنت الأشياء.