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The Potential Future of Urban Digitalization and Its Security Challenges

Elif Yilmaz^{1*}, Mehmet Demir¹, Ayse Kaya², Hasan Aydin¹

Abstract

To effectively respond to ongoing global shifts—including globalization, climate change, and population expansion—contemporary urban areas need to integrate digital technologies into their governance and operations. This study explores a framework for urban digitalization, drawing inspiration from the digital twin initiative implemented in Rotterdam. It outlines data-handling approaches suitable for diverse data origins. The discussion also covers associated cybersecurity vulnerabilities and the possible exploitation of smart city infrastructure for military purposes. Finally, by examining publicly accessible datasets on air quality monitoring and electricity use in public lighting, the study compares the functional capabilities of Rotterdam's digital twin with those of the digital platform developed for Brno. The analysis reveals that each municipality adopts a distinct digital transformation strategy, making a standardized, universal model impractical. Consequently, urban digitalization remains highly context-specific and individualized. At present, both platforms primarily enable the visualization of aggregated urban data. However, neither has yet incorporated sophisticated capabilities, such as artificial intelligence-supported decision-making or predictive modeling of urban phenomena. Nevertheless, they generate valuable datasets that hold significant potential for external stakeholders and third-party applications.

Keywords Digital twin, Smart energy, Smart solutions, Digitalization, Sensors, Security

*Correspondence:

Elif Yilmaz

elif.yilmaz@itu.edu.tr

¹ Department of Power Systems and Smart Grids, Faculty of Engineering, Istanbul Technical University, Istanbul, Turkey

² Department of Energy Analytics, Faculty of Engineering, Middle East Technical University, Ankara, Turkey

Introduction

Digitalization refers to the broad integration of digital tools and systems into routine activities and processes [1]. When applied to urban environments, it drives faster progress. It enhances quality of life across multiple domains, including energy systems, local economies, residential planning, civic participation, transportation, waste handling, healthcare delivery, and natural resource stewardship [1].

This transformation has also spurred the emergence of innovative paradigms, notably the Internet of Things (IoT). An IoT ecosystem comprises hardware components, software elements, and connectivity infrastructure. Its typical structure consists of three tiers: the perception tier (which involves sensors and actuators that interface directly with the physical environment [2]), the network tier (which handles data transmission between edge devices and gateways), and the application tier (which delivers user-facing services and functionalities) [3]. Four distinct IoT architectural models tailored to smart city contexts are described by Bellini *et al.* [4]: (i) a fully centralized cloud-based model, (ii) a fog-based model involving distributed fog nodes that communicate both among themselves and with a central facility, (iii) an edge-centric model suited to low-latency, lightweight computations performed near the data source, and (iv) hybrid approaches that leverage proximity to minimize delays [2]. IoT is increasingly recognized as a foundational element enabling smarter, more sustainable urban innovation and development [2].

Urban digitalization introduces several technical hurdles. The rapid proliferation of sensors heightens requirements for energy-efficient operation and extended device longevity [5–8]. Platforms must manage enormous data volumes, making on-device preprocessing highly desirable to reduce transmission loads [9, 10]. Downstream analysis and interpretation of incoming data streams present additional difficulties [11], with processing possible across temporal, spectral, or latency-based domains [12].

Amid volatile energy markets, the shift toward intelligent, renewable, and sustainable energy systems has accelerated. Localized energy distribution must adapt instantaneously to fluctuating demand and unexpected disruptions. Beyond reactive measures for crises, proactive anticipation and prevention are essential. Sensor networks play a critical role in detecting anomalies [13], feeding real-time inputs into urban digital twins [14]. Insights derived from these systems support the rollout of intelligent applications, service enhancements, and environmental improvements that benefit both residents and ecosystems [15]. Originally developed for industrial process optimization within Industry 4.0, digital twin technology has since been adapted for city-scale modeling [16, 17], enabling spatiotemporal data representation, scenario simulation, and forecasting of urban system dynamics.

In the present era, urban digitalization is imperative rather than optional. At the same time, the expansion of connected intelligent systems introduces novel security vulnerabilities [18, 19]. Should adversaries compromise a municipality's sensor infrastructure, they could potentially weaponize it against essential services and critical facilities. A structured methodology is therefore required to evaluate and mitigate risks associated with deploying smart technologies [20].

Under the European Union's Horizon 2020 RUGGEDISED initiative, three demonstration ("lighthouse") cities—Rotterdam, Glasgow, and Umeå—collaborated with three follower cities—Brno, Gdansk, and Parma—to advance smart city concepts. This article examines Rotterdam's practical implementation and evaluates the corresponding progress and prospects in Brno, Czech Republic. While parts of the work constitute a literature review, others provide a comparative assessment with forward-looking insights, including military implications. Because urban digitalization must align with each location's unique physical, cultural, and social conditions, a one-size-fits-all template is unfeasible, leading to the emergence of distinct digital urban identities.

The paper's original contribution lies in outlining a versatile platform architecture that underpins Rotterdam's operational 3D digital twin model. Given the divergent paths taken by Rotterdam and Brno, the study contrasts their respective approaches. Its timeliness stems from addressing smart city development through the lenses of cybersecurity and the potential repurposing of sensor-derived intelligence by military forces. Security considerations should be embedded at the design stage, with early threat identification and appropriate countermeasures.

The methodology encompasses:

- Establishing a core architectural blueprint for municipal digital platforms
- Specifying strategies for managing incoming heterogeneous data
- Cataloging potential cybersecurity threats
- Exploring emerging directions and military applications
- Conducting a side-by-side evaluation of Rotterdam's and Brno's digital systems

Related Works

Over the past decade, the topic of municipal digital transformation has attracted considerable academic and practical interest, as evidenced by numerous studies on intelligent urban solutions [21], IoT applications [13], broader digitalization trends [22], and digital twin implementations [23], among others. To map the current state of research, a search was conducted in the Web of Science database using terms such as “smart city”, “smart cities”, and “digitalization”. This query yielded 47,929 publications over the preceding ten years (Figure 1). Publication counts have plateaued in the most recent period, partly because newly released articles have not yet been indexed in the database.

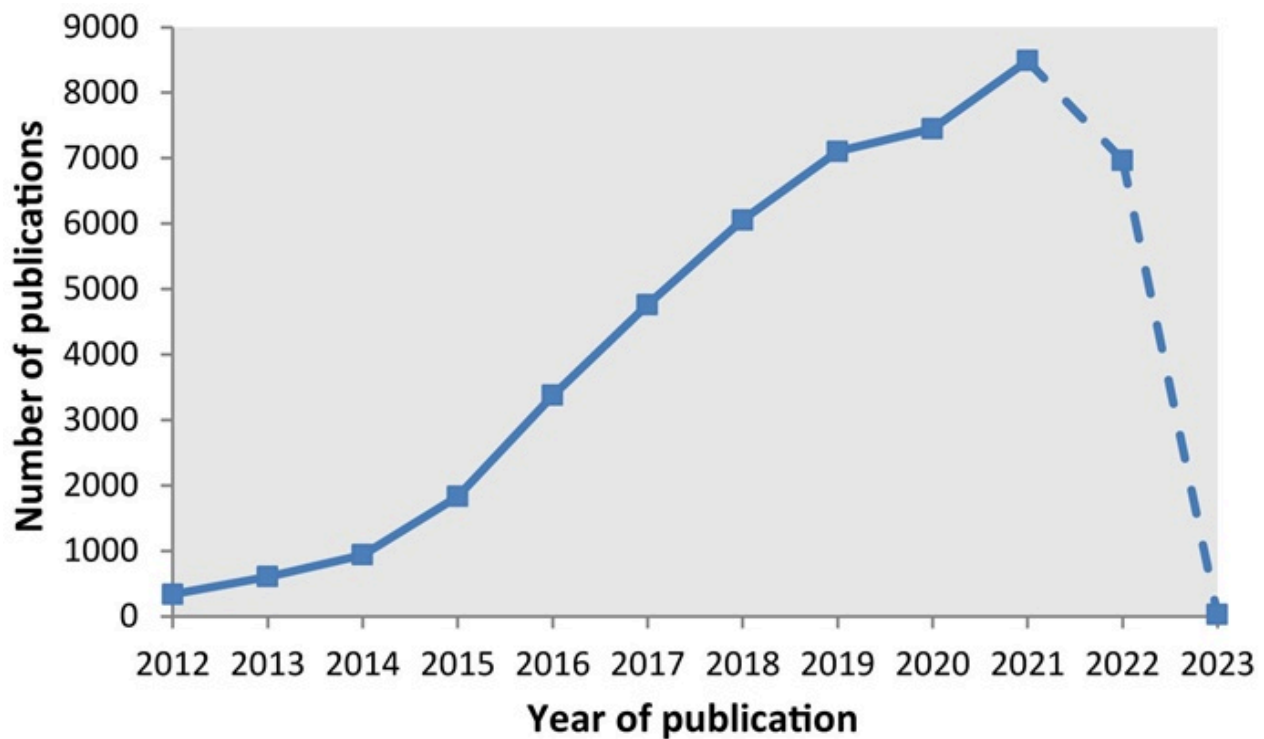


Figure 1. Number of publications focused on smart cities.

From fundamental theoretical ideas to the practical deployment of just a handful of sensors in buildings or along streets, the notion of a comprehensive digital twin for an entire city has evolved into a tangible reality.

The process of urban digitalization and the development of a city’s digital twin facilitates ongoing, real-time interaction between a virtual replica of the urban environment—continuously updated with live data streams from physical sensors—and the corresponding real-world physical components of the city [24].

Municipalities adopt different visualization approaches for their digital twins, most commonly either three-dimensional (3D) representations [25–28] or two-dimensional (2D) layouts [29]. Each format offers distinct strengths and limitations. A 3D model delivers a more intuitive and lifelike depiction of the urban landscape. Still, it can be more challenging to navigate and place greater demands on computing resources and user devices. In contrast, a 2D representation is generally simpler to operate and interpret, although it limits the user’s ability to grasp vertical relationships and overlapping urban layers.

An overview of comparable initiatives and research projects centered on digital twins or integrated urban data platforms is provided in Table 1.

Insights from the virtual urban model can enhance and optimize various facets of city operations and planning. Examples include the development and maintenance of green infrastructure, the integration of renewable energy sources,

improvements to municipal infrastructure, more effective urban construction and spatial planning, and overall elevation of residents' quality of life.

In one notable proposal, Ferré-Bigorra *et al.* [30] outline a unified architecture for an urban digital twin built around four core modules: mobility management, water management, energy management, and atmospheric monitoring combined with predictive capabilities. That said, many additional domains lend themselves to digital twin implementation beyond these four areas.

Table 1. Comparison of similar works.

Reference	Topic/Purpose	Visualization	Scope
[31]	Digital twin concept	-	City
[32]	Digital twin	3D	Infrastructure
[33]	Use a digital twin	3D	Port
[34]	Data platforms for smart cities	-	City
[35]	Developing a 3D digital model	3D	City
[36]	Taxonomy	-	City
[37]	Urban digital twin	3D	City
[38]	Web-based 3D smart city model	3D	City
[39]	3D city model of the park	3D	Infrastructure
[27]	Concept of digital twin	3D	City
[40]	Smart city data platform	-	City
[41]	Virtual 3D city model	3D	Campus
[42]	Digital twin of the park	3D	Infrastructure
[43]	Smart data platform	3D/2D	City
[44]	Smart city data platform	2D	Campus
[45]	Overview of digital twin	3D	Port

As cities continue to expand at an accelerated pace, the interplay between built urban spaces and human living conditions is growing increasingly complex.

A virtual geographic environment platform, described by Lin *et al.* [46], supports urban modeling and simulation efforts. That same work introduces the intriguing idea of the “metaverse,” highlighting the seamless interplay and mutual influence between human actions in physical reality and in virtual spaces.

Another forward-looking idea, the “Self-Organizing City,” appears in the work by Yun and Lee [47]. This concept envisions an optimal synergy among a city's digital twin, comprehensive cloud-based information, and active citizen involvement facilitated through mobile devices. In essence, the digital twin can serve as a powerful aid for informed decision-making while simultaneously fostering greater public engagement and participation.

In a study by Obi and Iwasaki [48], researchers outline an approach to smart governance in Japan that leverages a digital twin. As the intelligent building sector aligns with the goal of high-quality, sustainable growth, new possibilities emerge

alongside new challenges. Increasingly, climate resilience and environmental considerations must be embedded in building design and performance.

The notion of Intelligent Green Building (IGB) is advanced by Yang *et al.* [49], who argue that sustainability principles should permeate every phase of a structure's lifecycle—from planning and construction to ongoing operation and maintenance. Achieving this vision requires the deep integration of digital technologies and energy-related innovations across all stages. The study specifically examines how a city's digital twin can influence and improve the operation and maintenance phases of green buildings. Looking ahead, Caprari [50] explores the evolving role and potential of digital twins within the broader context of the Green Deal and sustainability priorities.

Digital twins hold considerable promise for the continuous monitoring and intelligent oversight of civil engineering infrastructure [51]. Research by Mahmoodian *et al.* [15] demonstrates that combining cutting-edge technologies such as IoT and digital twins can lead to substantial reductions in the cost of maintaining infrastructure assets. The resulting data streams enable advanced analysis and visualization, supporting maintenance planning, predictive modeling, and other uses. By interpreting these datasets, it becomes possible to generate reliable forecasts.

For instance, Henzel *et al.* [52] focus on predicting next-day energy consumption in buildings using high-resolution data from a building-specific digital twin. The study evaluates several forecasting techniques—including the naive baseline, linear regression, long short-term memory (LSTM) networks, and the Prophet algorithm. The resulting predictive model helps lower overall electricity usage, better align photovoltaic generation with actual demand, and optimize the utilization of battery energy storage systems. The authors recommend focusing monitoring efforts on the building's major electricity-consuming devices and systems, as this targeted approach yields the greatest reductions per measurement point.

Although the implications of smart city technologies for national security and defense remain largely under-examined and uncertain, the widespread adoption of advanced systems in urban areas inevitably heightens exposure to cyber risks. Consequently, robust cybersecurity measures and the protection of personal privacy have become critical priorities today [53].

Possible cyber-attack vectors targeting smart city ecosystems are identified and examined in Lee *et al.* [54]. Ensuring the resilience of individual intelligent networks that form part of the larger smart city is equally essential. Several studies address the security challenges specific to IoT deployments [55, 56]. From a defense standpoint, key sectors such as critical utility services [57], transportation systems [58], and healthcare infrastructure [59] warrant particular attention.

In a study by Kovalsky *et al.* [60], the authors highlight the serious consequences that can arise from underestimating the vulnerabilities of interconnected urban systems during post-conflict stabilization efforts in networked cities. They put forward a structured methodology for identifying, evaluating, and mitigating risks associated with the deployment of smart technologies in urban settings.

At the same time, the ongoing digital transformation presents valuable opportunities for the defense community. Fiott [61] illustrates how digital innovations can enhance both operational effectiveness and technological independence for European military forces. Similarly, Johnsen *et al.* [62] explore potential military applications of IoT technologies.

City Digitalization Framework

The foundational architecture of a comprehensive city digital twin relies on real-time data visualization sourced from a central hub, most often called the Urban Data Platform (UDP). Through immersive 3D city representations, it becomes significantly easier to interpret spatial patterns, temporal dynamics, and the complex interdependencies among people, physical infrastructure, and technological systems [63].

As outlined by Diran *et al.* [63], the UDP is structured into two primary tiers: a supply layer and a demand layer (Figure 2). The supply layer aggregates inputs from a wide array of heterogeneous data sources, while the demand layer encompasses the datasets and services made available for downstream applications. Acting as the vital intermediary, the UDP collects, processes, harmonizes, stores, distributes, visualizes, and analyzes information generated by individual smart city initiatives.

To enrich the overall picture, data gathered through municipal channels can be augmented with external, non-governmental sources. The conceptual model depicted in Figure 2 provides a practical blueprint for guiding the initial design of a digital city platform and for defining and organizing its constituent subsystems.

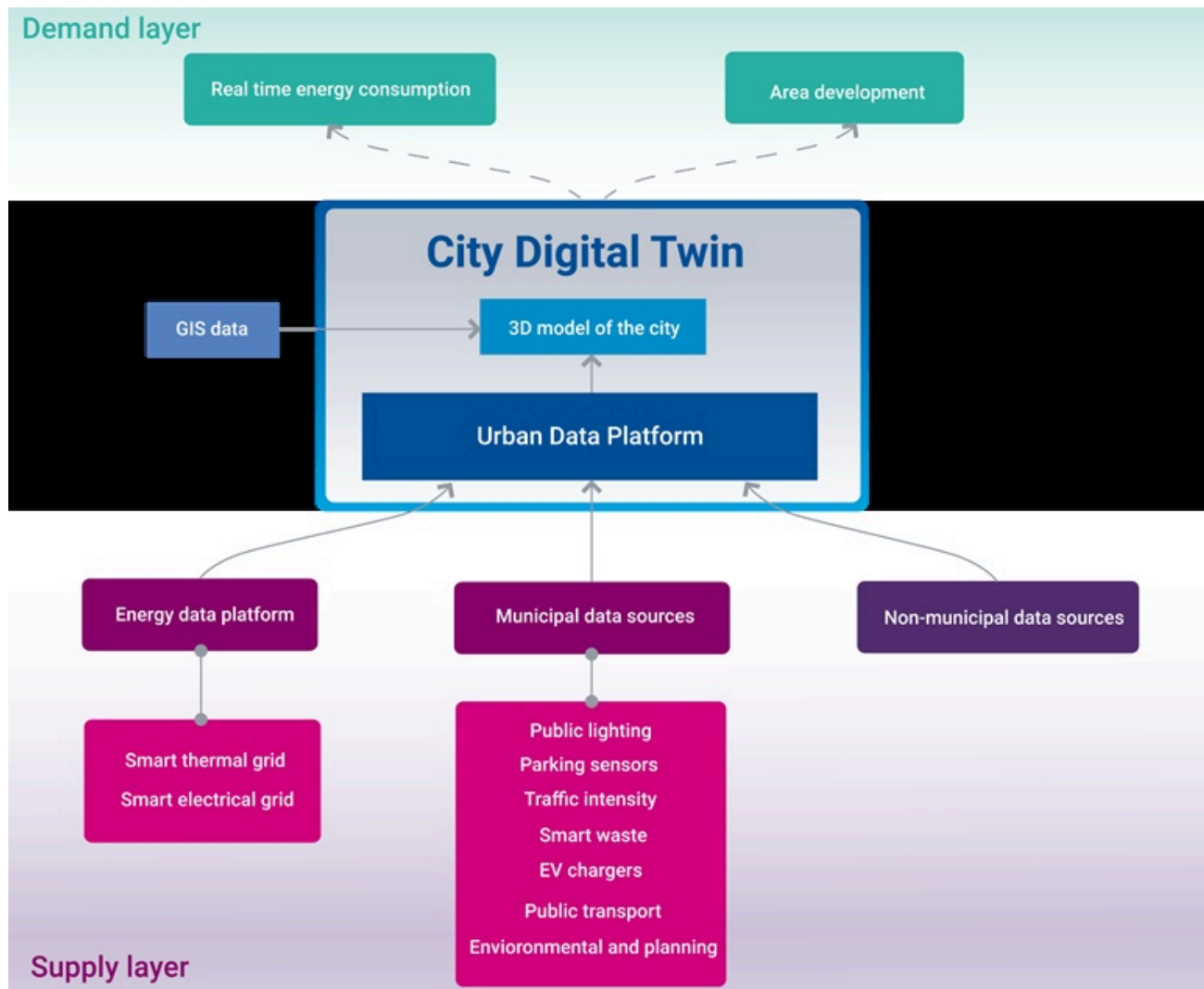


Figure 2. Architecture of the city digital twin platform.

A holistic, up-to-date representation of the city's current condition forms the foundation for well-informed decision-making across numerous municipal domains, establishing one of the central functions of the Urban Data Platform (UDP).

Schieferdecker *et al.* [64] outline the principal categories of insight that can be derived from the UDP:

- Operational — detailed characteristics of urban assets and ongoing activities, along with identification of practical opportunities for optimization and enhancement.

- Critical — continuous surveillance of conditions coupled with the generation of recommendations for responding to incidents, emergencies, or crises.
- Analytical — detection and evaluation of recurring patterns, which then enable the formulation of forward-looking predictions related to urban development and innovation.
- Strategic — support for aligning long-term objectives, actionable plans, and concrete decisions within the complex urban context.

Because the UDP ingests information from a highly diverse array of sources, inconsistencies in format, structure, semantics, or quality are common and can significantly complicate downstream processing and utilization. For this reason, careful preprocessing, transformation, and harmonization of incoming data streams are essential before they are integrated into the platform.

The most straightforward path would be to adopt a single, universally agreed-upon data standard that every provider would adhere to; unfortunately, achieving such uniformity across heterogeneous stakeholders remains highly challenging in practice.

An alternative approach, focused on secure data ingestion and controlled publication while safeguarding privacy, is illustrated in **Figure 3**. This conceptual framework draws inspiration from the model proposed by Liu *et al.* [65].

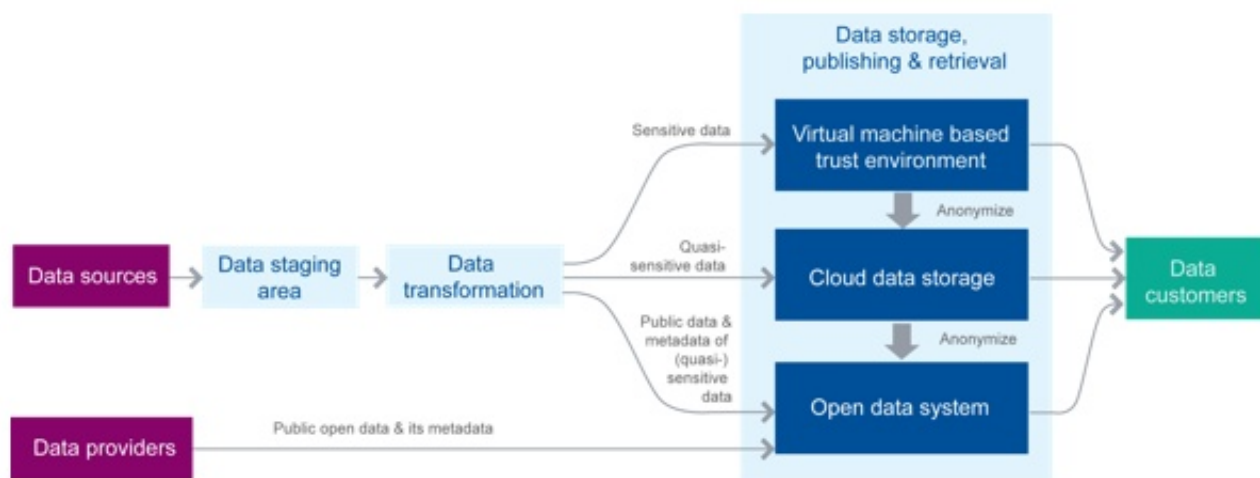


Figure 3. Overview of the data management architecture.

Data streams from various sources—such as sensors, smart meters, Internet of Things devices, traffic monitoring systems, meteorological records, and air quality sensors—are initially routed to a holding zone, the staging area. Within this zone, any gaps or missing values are filled in where possible, and information from different feeds is integrated or aligned as needed. The data-transformation stage then reformats everything into a structure optimized for UDP-based transfer and subsequent analysis workflows. Next, cleansing routines are applied to improve quality, and during this phase, all personally sensitive elements must be located and flagged. Finally, before the information is released to the requesting party, it is categorized by sensitivity level, and appropriate anonymization procedures are applied.

Cybersecurity Risks and Digitalization Benefits in the Military Domain

At their core, smart cities represent a fusion of information systems, operational technologies, and networked communication infrastructure. Every constituent part can harbor exploitable weaknesses, exposing the ecosystem to persistent cyber threats. The fundamental objectives of cybersecurity defenses are to block unauthorized disclosure of information, eliminate service interruptions, and prevent disruptive latency or slowdowns. Meeting these goals demands protection not merely of isolated elements but of the complete interconnected environment—an undertaking that is inherently complex and demanding.

Risk management must commence with a structured risk evaluation, conducted formally or informally. In most organizational settings, a formal risk assessment follows a four-step methodology: cataloging critical assets, evaluating potential risks and threat scenarios, identifying weaknesses or pre-existing conditions that increase exposure, and reviewing current safeguards and estimating risk probability (Figure 4).

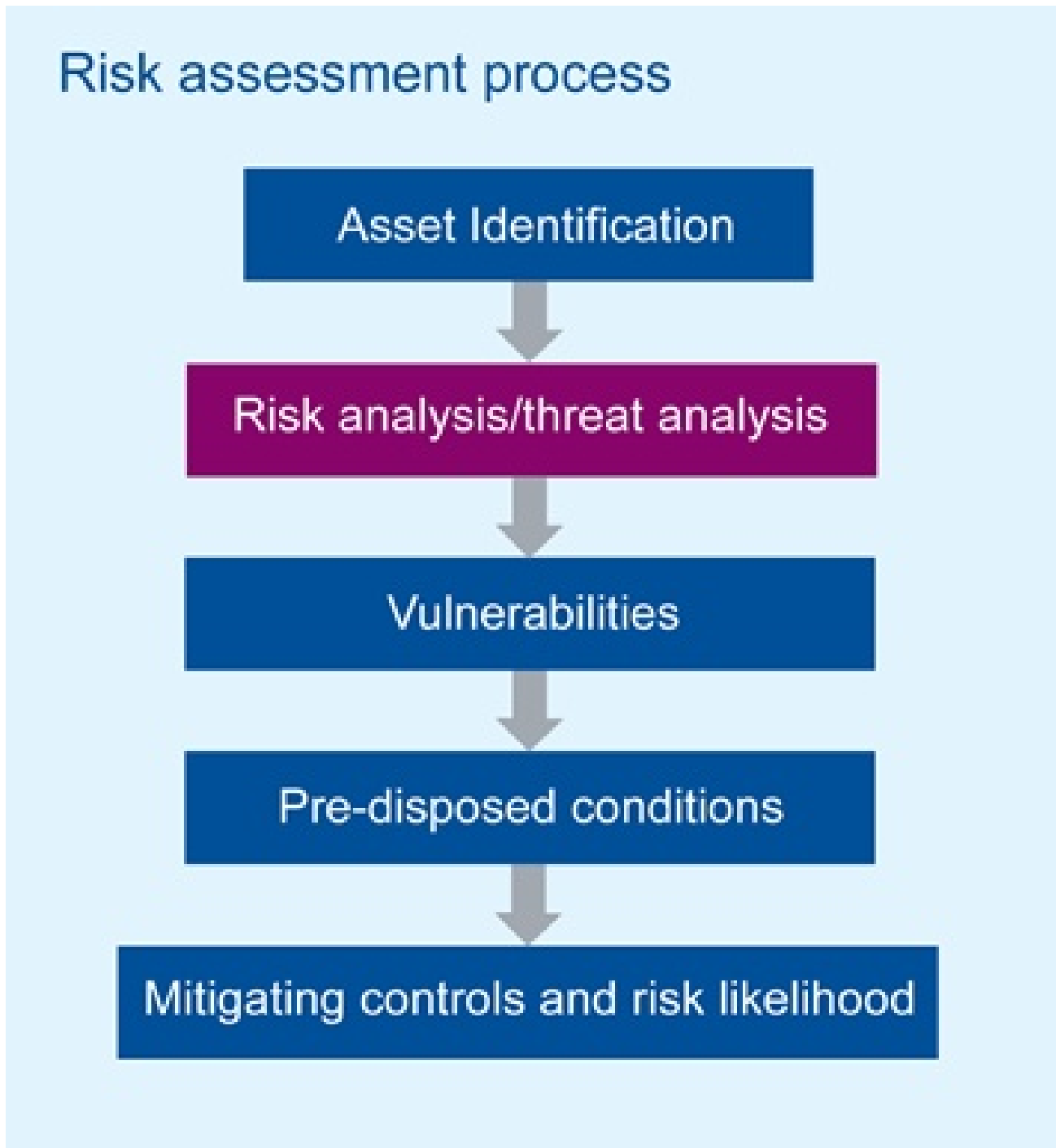


Figure 4. Risk assessment process.

Various established classification frameworks exist for evaluating security risks and pinpointing potential dangers. These frameworks facilitate a precise understanding of threats, both within an organization and among experts with varying viewpoints [66].

The Open Threat Taxonomy (OTT), released in 2015, addresses a broad spectrum of risks affecting the functioning of information systems. It organizes 75 distinct threat actions into four primary groups: threats related to physical security, threats to resources, threats involving personnel, and threats of a technical nature.

In 2016, the European Union Agency for Network and Information Security (ENISA) released its threat taxonomy, which organizes risks into eight overarching categories: Physical Attack, Unintentional Damage, Disasters, Failures/Malfunctions, Outages, Eavesdropping/Interception/Hijacking, Nefarious Activity/Abuse, and Legal Issues. Each of these broad categories is further broken down into more specific threats, complete with explanatory details.

The National Institute of Standards and Technology (NIST), in its guidance on performing risk assessments, simplifies the classification by grouping threats into just two main types: adversarial threats (those driven by intentional actors) and non-adversarial threats (those arising from accidental or environmental factors).

Here are some key examples of risks specifically affecting sensors and cloud-based environments [67]:

- Breach of confidentiality and integrity: Access to stored sensor information must be restricted to authorized devices alone. Unauthorized access can lead to tampering with the data's accuracy and reliability.
- Interception of communications (eavesdropping): Data transmitted between sensors and gateways can be vulnerable if channels are not properly secured. Unauthorized parties may capture transmissions, leading to data distortion, alteration, or disruption of system operations.
- Loss of data: Attackers could steal or cause the disappearance of critical information, severely impacting smart city services.
- Disruption of availability: Proper strategies and backup measures are essential to handle potential sensor breakdowns and minimize adverse effects on urban functions. Without such preparations, sensor outages might create hazardous or chaotic scenarios.
- Unauthorized remote access and exploitation: Given that sensor networks connect to central servers, attackers might exploit software flaws or legitimate credentials to infiltrate internal systems, execute malicious code, and seize control.

Smart city sensor information is typically hosted in the cloud for convenient access by various users. Since cities often rely on external third-party cloud providers rather than managing their own infrastructure, stored data faces additional vulnerabilities [67]:

- Risk of data exposure or leakage: Outsourcing data management to a third party means the city relinquishes direct oversight, increasing the chance that adversaries could steal sensitive information.
- Vulnerable application programming interfaces (APIs): Cloud interactions with user-facing applications depend heavily on APIs, which must incorporate strong security measures for safe data exchange.
- Threats from malicious insiders: Employees at cloud providers might mishandle or improperly access client data, even if background screenings are performed.
- Denial of Service (DoS) attacks: Reliance on an external provider means that targeted DoS campaigns could render the smart city platform temporarily unusable or unreachable.
- Injection of malicious software: Cloud environments can be susceptible to attackers uploading harmful applications that blend in with legitimate ones and execute within the infrastructure.
- Weaknesses in systems and applications: With data handling outsourced, the city depends entirely on the provider's security practices and trustworthiness, necessitating thorough vetting of the service supplier.

As outlined by Ma [53], smart city cybersecurity can be undermined through various attack vectors, including malware (such as viruses, trojans, ransomware, spyware, adware, and botnets), SQL injection attacks, phishing attempts, man-in-the-middle interceptions, denial-of-service incidents, and social engineering tactics. A visual overview of all relevant cybersecurity risks in the context of a city's digital twin is presented in **Figure 5**.

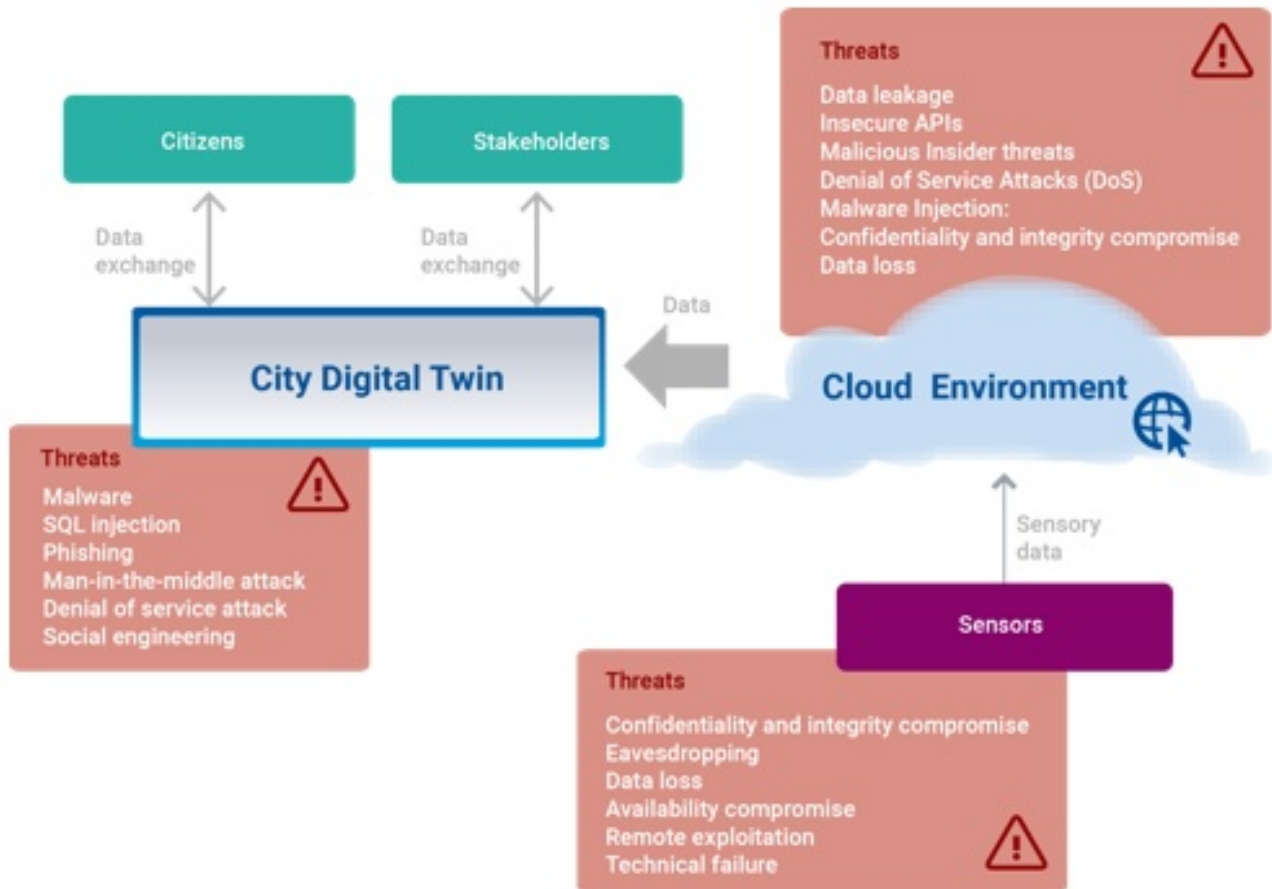


Figure 5. An overview of potential cybersecurity risks associated with the digital twin of a city.

Griffor [68] outlines certain approaches to countering threats in smart city systems. These countermeasures fall into two broad categories.

The first category emphasizes IT-oriented defenses, including:

- Implementing robust anti-malware protections
- Regularly assessing vulnerabilities across various elements of intelligent infrastructures
- Launching ongoing user education initiatives based on established best practices
- Providing regular cybersecurity training to staff members
- Continuously monitoring devices in older smart setups
- Recognizing possible conflicts or mismatches in security measures from different vendors

- Protecting data flows over networks through virtual private network (VPN) usage
- Restricting smart devices from transmitting solely essential operational or critical information, avoiding unnecessary sharing of private user details
- Employing public key infrastructure mechanisms to safeguard data exchanges
- Developing and deploying systems to detect and block network intrusions
- Enforcing access rights exclusively through appropriate authentication methods and secure protocols.

The second category addresses defenses against physical risks, such as:

- Constructing durable and protected physical networks along with secure foundational setups
- Safeguarding equipment both internally and externally
- Utilizing protective gear and enclosures
- Adopting devices engineered with inherent security features that resist tampering
- Maintaining reliable installation and ongoing upkeep of monitoring systems
- Performing routine inspections of all physical hardware components.

Additionally, it is essential to classify specific segments of a smart city as either key information systems or critical infrastructure elements. Such classifications require adherence to applicable legal standards and requirements. At the same time, existing laws must adapt and advance in response to the ongoing evolution of smart urban environments.

Military applications

The engineering and architecture of a smart city must also account for national defense considerations from two angles:

- Preventing adversaries from exploiting the city's technical systems to aid their offensives. This would typically require them to first compromise the smart city network via a cyber intrusion to assume command over control mechanisms.
- Leveraging the city's technical framework to bolster territorial defense during an enemy assault.

The risks of enemy exploitation of urban technical assets are thoroughly covered by Kovalsky *et al.* [60]. Chiefly, this involves harvesting intelligence via citywide sensors and subsequently triggering widespread disorder and fear to hamper defensive efforts.

Conversely, employing the infrastructure for self-defense focuses on linking smart city systems with military command-and-control frameworks. During armed conflicts or major natural calamities, contemporary urban areas face severe destruction of residential zones and essential services. In these crises, military assistance for search, rescue, and restoration operations proves invaluable and highly efficient. Nonetheless, the priority lies in preempting and mitigating such events within city settings. According to Pradhan [69], military involvement can be conceptualized across three main axes:

1. Direct deployment of forces into the urban combat zone, primarily relying on ground troops backed by aerial and armored units.

2. Remote intelligence, surveillance, and reconnaissance (ISR) activities to establish and sustain up-to-date battlefield awareness, vital for orchestrating countermeasures and recovery.
3. Long-range neutralization of threats by infantry or air assets providing extended support.

According to Pradhan [69], military utilization of smart city assets can occur in several domains:

- Building-integrated sensors supplying readings on air composition, chemical agents, smoke, radiation, or hazardous gases to detect leaks, blasts, or adversarial actions.
- Advanced traffic control platforms enabling rapid routing of ground forces through contested zones for swift maneuver.
- Smart electrical grids and energy distribution networks allow power prioritization and management amid disruptions or limited availability. Military units could tap distributed smart hubs as backup power sources for equipment charging, while also using grid capabilities to restore electricity to vital civilian services via auxiliary generators.
- Sensors monitoring water purity to identify any tampering or contamination in municipal supplies.

Incorporating digital tools markedly enhances the preparedness and operational effectiveness of military units. Simultaneously, the extensive networking of communications, sensors, supply chains, and decision-making centers imposes substantial requirements on cybersecurity defenses, which now form a cornerstone of military resilience [61]. For optimal synergy, the technological frameworks of smart cities and the armed forces must be aligned and co-developed to avoid compatibility issues. Only under such conditions can the full advantages of integrating smart urban tech with military operations be realized.

Rotterdam vs. Brno Implementation State

Rotterdam

As part of its push toward sustainable transport, Rotterdam has rolled out fleets of electric buses. These vehicles recharge using solar energy captured by photovoltaic panels installed atop sizable structures. Combined with route and schedule optimizations that align with charging windows, this approach has markedly lowered nitrogen oxide (NOx) pollution levels across the urban area [70].

Intelligent waste collection has delivered measurable benefits, such as a 20% reduction in collection vehicle travel distance, fewer trips and optimized routes, reduced bin overflows, lower CO₂ emissions and noise pollution, and notable reductions in fuel consumption, operational time, and expenses. These gains stem from fill-level sensors in containers that feed data into algorithms for planning the most efficient truck routes.

Significant further cuts in energy use and carbon emissions are anticipated from upgrading to advanced, adaptive street lighting systems. Features include automatic fault alerts from individual fixtures, centralized maintenance coordination, and remote adjustment capabilities (such as dimming LEDs in response to natural light conditions or local events), all of which enhance efficiency and responsiveness.

These various intelligent initiatives have been implemented across Rotterdam, with their real-time sensor and telemetry data integrated into the municipality's digital twin platform.

Rotterdam is currently advancing a comprehensive 3D operational city model that is still in the proof-of-concept stage. As detailed in the implementation documentation [71], authentic parking occupancy information has been effectively incorporated and displayed within this 3D environment. Live feeds covering road traffic, public transit movements, and bridge openings are also accessible in the model.

The 3D representation encompasses multiple thematic layers depicting diverse aspects of urban infrastructure, including roadways, waterways, canals, and public illumination networks.

The city features extensive subterranean elements (such as pipelines, power cables, metro tunnels, and other subsurface facilities). Incorporating detailed mappings of these into the 3D model streamlines tasks like infrastructure planning for new developments or coordinating responses during crises.

Information on urban expansion projects and specific building profiles forms another layer. Future expansions may include granular interior layouts of tall structures to aid emergency responders, such as firefighters, during incidents.

An additional component involves comprehensive tree inventory data, cataloging every tree across municipal boundaries. Real-time traffic updates support quick resolution of disruptions. The model also serves as a planning tool for upcoming construction projects. Through augmented reality features, residents can preview proposed structures or green spaces by scanning QR codes at development sites, which overlay virtual previews onto the real environment.

Figure 6a displays example views from the 3D city model, highlighting details for individual structures, such as construction year, floor count, and basement levels. **Figure 6b** showcases infrastructure layers, including streets, electrical grids, telecom networks, water mains, and sewer systems.

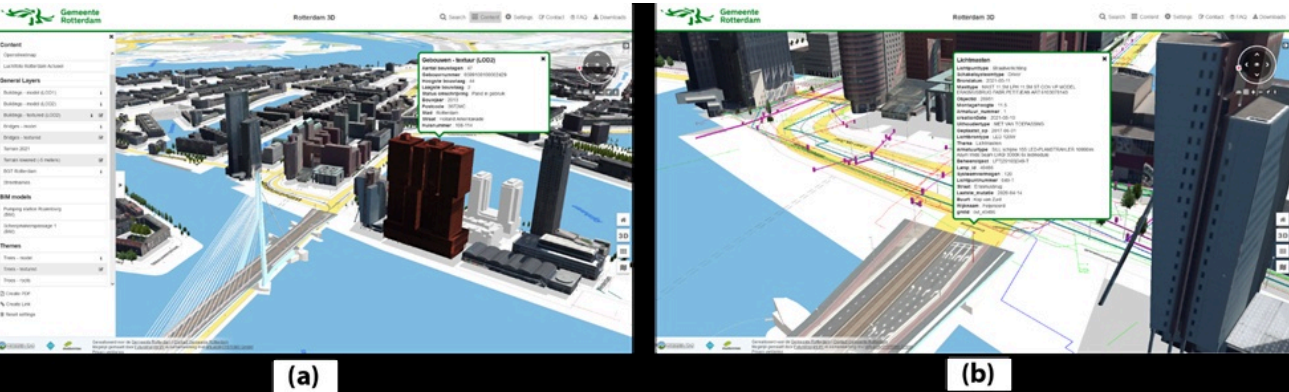


Figure 6. Rotterdam's 3D city model, serving as its digital twin: (a) Close-up view from the 3D application displaying detailed building attributes. (b) Infrastructure overlay layer highlighting public lighting fixtures [72].

Brno

The municipality of Brno operates an open web-based data portal called data. Brno [29]. At present, this platform hosts 143 distinct datasets, with new additions added regularly. Examples include real-time information on road traffic (sourced from Waze for Cities), air pollution levels (covering PM10, PM2.5, ozone, and NO₂), positions of public transit vehicles, bicycle movement patterns, and parking space availability. Many of these datasets receive continuous updates.

Beyond purely technical topics—such as traffic flow, street lighting, waste collection, and recycling—the available data also span areas like local economy, historical records, environmental conditions, education, public safety, and public health. By openly sharing and digitizing municipal information, the city fosters an environment conducive to the emergence of startups and innovative enterprises that can leverage data insights and analytics.

This broad visibility into municipal operations enables rapid cost reductions and improved efficiency in delivering public services. From a societal perspective, the platform encourages community building and greater citizen participation in local governance. Ultimately, it supports the development of a holistic understanding of specific urban areas, integrating social and economic dimensions alongside physical attributes.

All datasets are freely accessible and open, empowering users to conduct their own analyses or connect via APIs to build custom tools, applications, and services.

Currently, data visualization is limited to 2D mapping interfaces (Figure 7), and there are no announced intentions to integrate these datasets into a full 3D city model. The city's existing 3D model is a standalone tool that primarily incorporates elevation data for structures and an inventory of urban trees.

Notably, the datasets exclude details on critical infrastructure components (such as water supply networks and electrical grids) and any personally sensitive information. This deliberate omission significantly reduces the potential for harmful data exploitation.

In the realm of sustainable energy, the portal features a dedicated map showing photovoltaic (solar) potential across the city. This resource helps residents assess the suitability of building rooftops for solar panel installation by illustrating sunlight exposure patterns [73].

The underlying solar radiation calculations for Brno were performed by TopGis, s.r.o., based on the 2019 digital surface model of the city (derived from stereophotogrammetry) at a 1-meter resolution. Computations cover every day of the year, with values aggregated at half-hour intervals. Each grid cell reflects the total annual sum of direct and diffuse solar radiation, expressed in kilowatt-hours (kWh).

Additional datasets provide locations and specifications of electric vehicle charging stations as well as hubs for shared micro-mobility services.

Figure 7a depicts the Brno data platform with the public lighting dataset activated. Individual points on the map represent street lamps and include attributes such as lamp type, wattage, pole design, installation date, and precise geographic coordinates—demonstrating how users can layer and explore various datasets within the interface.

Figure 7b presents the solar radiation intensity map for Brno, which is also available in the data. Brno platform. For each building shown, the map indicates the rooftop area, along with average, minimum, and maximum annual solar radiation values (kWh/m²/yr).

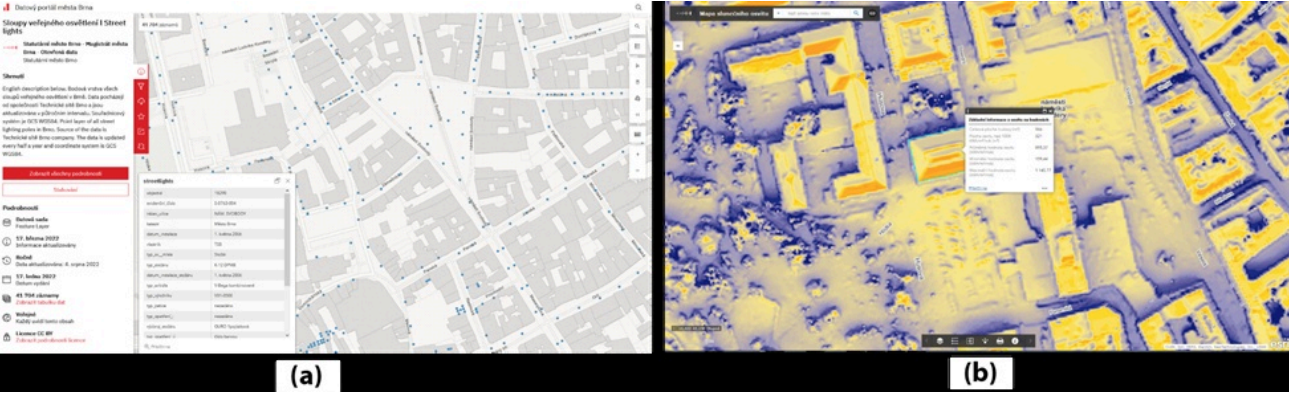


Figure 7. The data.Brno city data platform: (a) Dataset of public lighting with information about lamps. (b) The map of solar radiation intensity [29].

Comparison of urban data portals

A side-by-side evaluation of the two municipal data platforms is provided in Table 2, which highlights and contrasts their primary characteristics.

The most prominent distinction lies in how the datasets are visually represented. Rotterdam employs a sophisticated 3D visualization approach, whereas Brno relies on a conventional 2D mapping interface.

Rotterdam's platform capitalizes on its three-dimensional model to offer enhanced opportunities for citizen engagement. Residents can take part in upcoming urban projects by casting votes, submitting comments, and experiencing proposed developments through augmented reality overlays. The system also supports selective viewing of individual infrastructure layers, enabling detailed examination of subsurface utility networks—including electrical and telecommunications cables, water supply and sewer lines, and metro tunnels.

In contrast, Brno's data portal lacks 3D capabilities and augmented reality features. However, it compensates by providing access to records and materials from city council meetings, thereby keeping citizens informed about local political decision-making processes.

A key strength of the Brno platform is its robust support for data export and integration. Users can regularly retrieve datasets via an API for incorporation into custom-developed applications and tools. Additionally, the portal allows interactive exploration of individual datasets overlaid on a 2D map, along with access to built-in advanced analytical applications for deeper insights.

Regarding real-time or sensor-derived data, both platforms currently provide only a modest range of functionalities. These include visualization of public transport vehicle locations, reports of traffic incidents, measurements of air quality parameters, cyclist counts from dedicated bike detection sensors, parking garage occupancy levels, and—in the case of Rotterdam—status updates on bridge openings.

Table 2. Smart city platforms comparison.

	Rotterdam	Brno
Visualization	3D	2D
API for downloading the data	No	Yes
Possibility of participation	Yes	No
Augmented reality	Yes	No
Underground layers	Yes	No
Information from the city council	No	Yes
Real-time datasets	Yes (limited)	Yes (limited)
Additional applications and further analysis	No	Yes

Valuable insights into the comparison between the two cities can be derived from existing datasets. One key indicator of progress toward smarter urban solutions is improved air quality. As illustrated in [Figure 8](#), the annual mean overall Air Quality Index (AQI) [74] for Rotterdam and Brno reveals distinct differences. Brno's pollution levels fall within the yellow "Moderate" category, whereas Rotterdam consistently remains in the green "Good" range. Note that the 2022 data covers only the first six months. Recent years in Brno have also seen somewhat worse air quality, potentially due in part to ongoing construction projects in the central urban area.

To address this challenge, Brno might consider adopting strategies similar to those implemented in Rotterdam, particularly by placing greater emphasis on electric buses. At present, however, the Brno Transport Company has no plans to acquire electric buses. In recent years, the company has prioritized transitioning from diesel to CNG-powered buses. Furthermore, approximately two-thirds of its fleet already operates on electricity through its tram and trolleybus

systems. This approach has been shaped by prevailing economic constraints, as well as concerns about the limited range of electric buses and the insufficient charging infrastructure at depots and terminals.

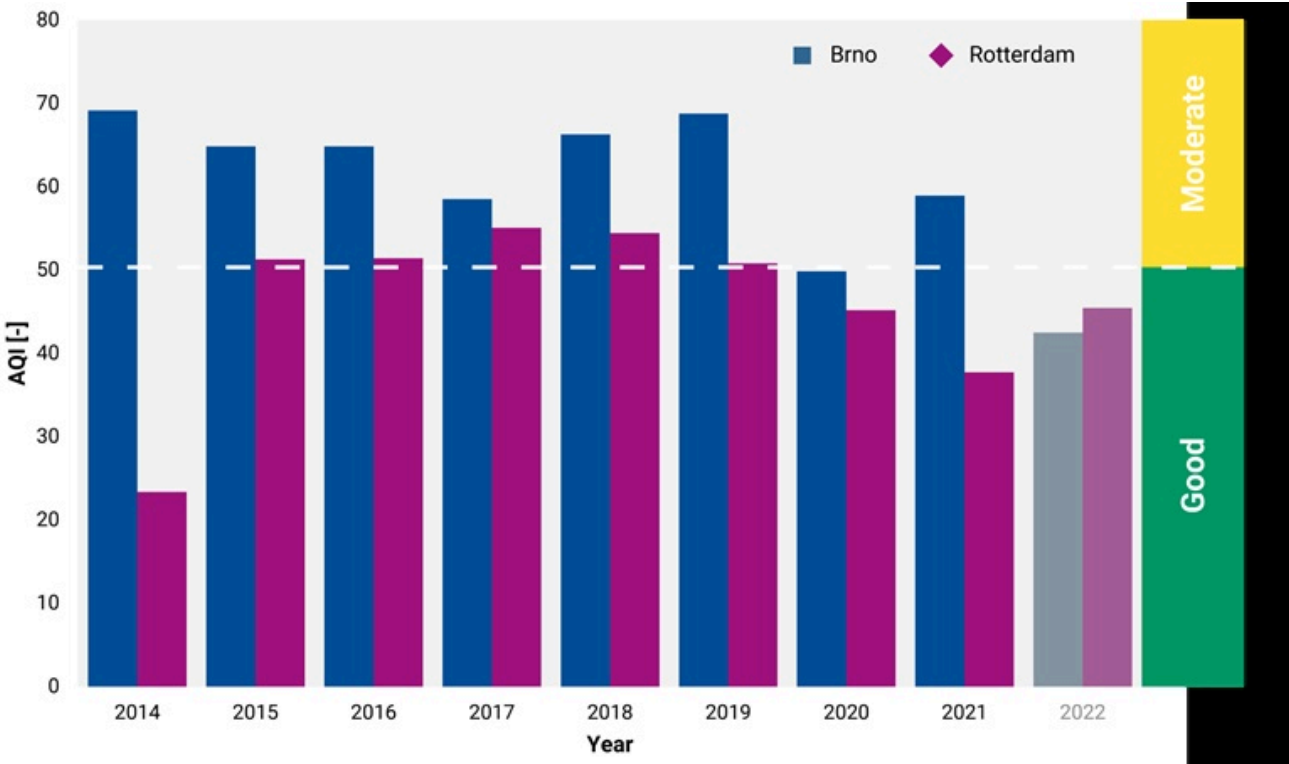
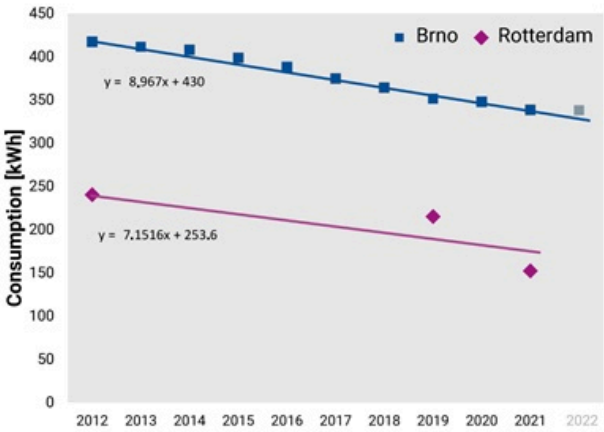
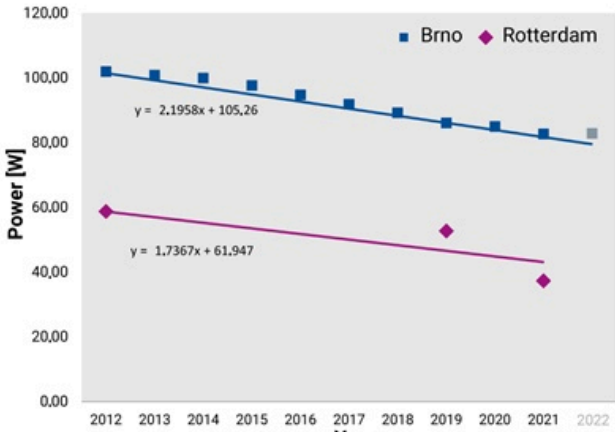


Figure 8. Year average overall Air Quality Index (AQI) for the city centers of Brno and Rotterdam.

Another aspect of evaluating the two cities involves electricity usage for public street lighting. **Figure 9** compares total annual electricity consumption with average power consumption per lighting point. The data indicate that Brno's average power per light point stands at approximately 80 W, while Rotterdam achieves roughly half that figure. In Brno, LED luminaires account for 11% of the public lighting inventory, compared to 60% in Rotterdam. Rotterdam has set a goal to convert its entire street lighting network to LED technology by 2025. Meanwhile, Brno has outlined a phased transition to LED fixtures, targeting a 13.5% share through installations scheduled for 2023.



(a)



(b)

Figure 9. Public lighting consumption for Brno and Rotterdam: (a) Consumption per single light point, and (b) Power per single light point.

Regarding the deployment of intelligent public lighting, Brno employs the DALI protocol to facilitate communication between street lamps and the central control center. Control occurs via around 400 switching stations that connect to the dispatch office through a dedicated radio network. Currently, dimming for reduced energy use applies to roughly 100 lighting points. As stated by Technical Networks Brno, there are no immediate plans to introduce advanced smart lighting equipped with additional sensors or widespread individual controllability.

The intent here is to offer concrete illustrations of digitalization strategies as applied in Rotterdam and Brno. In contrast to Rotterdam, which features sensory information visualized through a 3D city model, Brno restricts its presentations to 2D maps—an approach that proves more practical in certain scenarios. Through its data portal, Brno prioritizes releasing open datasets, empowering users to process, examine, and integrate the information into their own software and visualizations—potentially enhancing the data. The Brno portal might include incorporating a greater volume of real-time sensor feeds. Adding artificial intelligence for data analysis to develop forecasting models could also prove valuable. At present, Brno is rolling out various forward-thinking initiatives, including EV charging stations in housing districts, solar panel installations on structures at the Brno heating plant, a shift toward LED-based street illumination, brownfield redevelopment, extended sustainable waste strategies, and the development of a district heating pipeline linking the Dukovany nuclear facility to Brno. Over time, these measures are expected to elevate residents' living standards and advance reliance on renewable energy.

Results and Discussion

Within the framework of the RUGGEDISED initiative, municipalities like Brno would benefit from drawing inspiration from advanced European urban centers and adopting established smart city practices common in Western Europe. By juxtaposing Rotterdam's digital twin approach with Brno's, the analysis yields several key insights: while the digital twin model itself is transferable, its specific elements must be tailored to each city's unique context and priorities; each city must build its own version independently. The underlying digital platform provides a strong foundation for deploying innovations such as photovoltaic systems, adaptive street lighting, and electric vehicle integration.

Moreover, given the evolving instability across Eastern Europe, questions arise about how urban digitalization might safeguard residents or, conversely, expose municipal systems to vulnerabilities that adversaries could exploit. To mitigate such risks, appropriate safeguards are essential, as outlined briefly: smart city frameworks and defense-related technologies should evolve in coordination; the extensive linking of communications, monitoring, supply chains, and operational centers demands robust cybersecurity; security considerations and risks of misuse must be embedded from the initial design of hardware components (IoT devices, gateways, sensors) and software layers (cloud environments, online interfaces); critical systems and infrastructure must comply with applicable legal standards.

Insights and lessons drawn from implementations in Rotterdam and Brno can inform the preliminary design of a municipal digital platform.

Future Trends

The core driver of urban digitalization should remain the enhancement of livability and the centrality of people [75-77]. A prominent emerging focus for tomorrow's smart cities involves eco-friendly design of public areas. Globally, cities release thermal maps that highlight temperature differences between vegetated and built-up zones. Such data ought to spur efforts to curb greenhouse gas outputs, lower urban heat in cores, and bolster ecological stability. Another key direction is fostering healthy environments for residents while helping residents, businesses, and agencies adopt digital health tools [78]. These tools enable proactive interventions for populations and curb detrimental habits, ultimately boosting well-being, longevity, and access to medical resources.

A vital element is advancing the “15-minute city” model alongside smart, eco-conscious transport options. Cutting vehicle dominance in central districts while encouraging electric options, shared mobility, and intelligent systems remains crucial for future urban development. Nurturing creativity and digital shifts via structures such as innovation centers and data use helps tackle pressing municipal challenges by making information accessible.

Further evolution includes the construction of environmentally sound structures and intelligent, durable infrastructure. Emerging central-area projects should utilize eco-materials and achieve high energy performance. Such buildings ought to generate their own power from renewable sources, such as solar arrays. Community backing for these developments is equally important. Engagement platforms can serve as channels for sharing project details and gathering input, thereby distributing accountability for urban initiatives among residents and authorities.

Digital platforms hold strong potential for AI-driven optimization of city functions, forecasting, and graphical data portrayal. They also enable evidence-based governance. Cybersecurity is a cornerstone of future smart city planning, given the proliferation of connected devices. Leveraging smart infrastructure to combat crime or respond to disasters is a timely and forward-looking application, in which defense entities might draw on sensor networks for strategic responses.

Conclusion

This paper outlines a conceptual structure for municipal digital transformation, informed by Rotterdam's practical experience. A major hurdle in digitalization is aggregating data from diverse sources into open, reusable formats for platform integration. Anonymization is vital to prevent exposure of confidential details from sources. The municipal digital platform thrives when driven by its users, who leverage available datasets—often from the digital twin—to build bespoke tools and solutions. The overarching aim of the digital city paradigm is to improve living conditions and environmental health while promoting sustainability by adopting clean energy.

The discussion also underscores a vital dimension of urban digitalization: ensuring cybersecurity. From a defense standpoint, the digital twin primarily aids in preparedness and planning. From a hostile viewpoint, it offers a rich intelligence resource that could be exploited for attacks. Thus, stringent protection is recommended, with access restricted via rigorous controls. During emergencies, military forces could harness citywide sensor data to address crises, whether natural or induced.

The paper compares the digital platforms of Rotterdam and Brno, detailing their functionalities and strengths. Key takeaways include:

- The architecture described in section three could form the foundation for a city's digital twin design.
- Before deployment, clear accountability for collected data is needed to foster confidence among the municipality, private sector, citizens, and academia. The local government should primarily oversee the platform and open data initiatives, with privacy and security guaranteed before ingestion. Standardized open data formats are necessary for seamless platform compatibility.
- Digitalization strategies vary by city and cannot be standardized universally. Rotterdam and Brno adopt distinct visualization methods; Rotterdam's complex, multi-level infrastructure (canals, bridges, subsurface elements) benefits from 3D representation.
- Risk evaluations must identify security vulnerabilities before digitalization begins, drawing on established classifications. The paper outlines prevalent threats in sensor-to-cloud setups.
- Data presentation is effectively handled on current platforms, yet AI-enabled tools for autonomous decisions and predictive management remain underdeveloped.

- Europe's present geopolitical context highlights opportunities to repurpose smart infrastructure and digital twins for civilian protection. Smart city designs and military systems must align to ensure seamless integration.
- The fundamental impetus for forthcoming developments is to render cities more humane and resident-oriented.

Abbreviations

The following abbreviations are used in this manuscript:

PV	Photovoltaic
NOx	The gases nitric oxide and nitrogen dioxide
CO ₂	Carbon dioxide
LED	Light-emitting diode
IoT	Internet of Things
AI	Artificial Intelligence
IGB	Intelligent Green Building
LSTM	Long Short-Term Memory
UDP	Urban data platform
GIS	Geographic Information System
NIST	The National Institute of Standards and Technology
SCCF	Smart Cities and Communities Framework
API	Application Programming Interface
PM ₁₀	Particulate matter that is generally 10 micrometers or smaller
PM _{2.5}	Particulate matter that is generally 2.5 micrometers or smaller
AQI	Air Quality Index

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Conflict of interest

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Ethics statement

None

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