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The World Avatar: A New Era in Digital Twinning for Sustainable Urban Development[#]

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ABSTRACT

This paper presents The World Avatar (TWA) as an evolution of connected digital twinning, founded on the idea of a general knowledge representation of the world at large. TWA adopts a unique approach to data integration, analysis, and, most importantly, the inclusion of the space of all possible concepts and world knowledge. More importantly, TWA serves as a dynamic framework for representing complex, evolving systems, supporting seamless human-machine interactions with diverse and dynamic data sources. To demonstrate these capabilities, we present four case studies across German cities, each of which highlights a specific complex urban challenge and demonstrates how TWA can interoperate across spatial, temporal, and real-time data to address these challenges. The case studies highlight the capabilities of TWA in supporting real-time decision-making processes, which are critical for urban sustainability and infrastructure development. This work demonstrates the significant advantages of TWA over conventional digital twin technologies, providing urban planners and policymakers with powerful tools to create more resilient, intelligent, and flexible systems for urban management. TWA shows the potential to equip cities with the capacity to enhance resilience and optimise infrastructure planning. This could enable cities to adopt sustainable, data-driven solutions and build more flexible, resilient, and intelligent urban infrastructure.

Keywords: Digital twins, Knowledge graphs, The World Avatar, Smart cities, Data integration, Ontologies

NOMENCLATURES

Abbreviations	
AI	Artificial Intelligence
ALKIS	Authoritative Real Estate Cadastre Information System
API	Application Programming Interface
CityGML	City Geography Markup Language
EV	Electric Vehicle
Gen-AI	Generative Artificial Intelligence
GIS	Geographic Information System
KG	Knowledge Graph
NASA	The National Aeronautics and Space Administration
TABULA	Typology Approach for Building Stock Energy Assessment
TWA	The World Avatar

1. INTRODUCTION

Digital twinning has gained significant traction in recent years, with notable developments such as Singapore's first maritime digital twin in 2025 [1]. This initiative aims to provide data-driven insights and visualisations that enable advanced maritime operations. Market analysts project a substantial increase in global expenditure on digital twinning, rising from USD 10.1B in 2023 to USD 110.1B by 2028 [2]. Digital twins and generative AI (gen-AI) can be combined to enhance their combined scalability, accessibility, and affordability, allowing organisations to improve their operations. Recognising this potential, 75% of large enterprises are actively investing in digital twins to scale their AI solutions [3].

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The concept of digital twins can first be traced back to NASA's Apollo program in the 1960s for real-time fault diagnosis during the Apollo 13 mission [4, 5]. Subsequent aerospace research expanded this approach to high-fidelity simulations of extra-terrestrial vehicles under communication constraints. After reintroduction in the 2010s, the concept transcended beyond the aerospace domain [6, 7]. As such, recent literature highlighted sector-specific implementations that integrate physics-based solvers with streaming sensor data to predict asset behaviour under varying operational conditions [8-11]. More recently, the evolution of digital twins has been examined, progressing from traditional methods (*ad hoc* data and model integration) to connected digital twins [12]. These developments emphasise the growing complexity and capability of digital twinning approaches.

Despite the potential of digital twinning, current digital twins often operate in isolation with limited scalability and interoperability [13-15]. Efforts to integrate digital twins are hindered by the difficulty of precise information exchange, with existing approaches offering only partial solutions. Reliance on single vendors risks lock-in, while extensive use of application programming interfaces (APIs) increases complexity [13]. Overcoming these limitations requires interoperability to enable tools and systems to share data and use each other's functionalities, which is essential for addressing cross-domain challenges [16]. Specifically, there is a need for a semantic description of all physical and digital components in the digital twins.

One of the means that can overcome these limitations is to adopt knowledge graphs (KGs) in the workflow. KGs are fundamental to the development of infrastructure for the forthcoming "smart" world [17]. This is because KGs enable connection and integration of disparate data and knowledge domains, fostering truly interoperable systems. KGs address data fragmentation and streamline integration, paving the way for urban data to be effectively utilised across applications. The World Avatar (TWA) exemplifies this approach, leveraging KGs to transcend the constraints of traditional digital twins, effectively connecting various data and knowledge domains to foster interoperable urban solutions [12, 18].

The purpose of this paper is to show the application of TWA in achieving interoperability across diverse urban system components. The use cases highlight the capability of TWA to overcome the limitations of conventional digital twins (*i.e.*, data silos, poor integration across domains) by integrating multiple data sources and supporting dynamic, real-time decision-making, thus providing actionable insights that would be unattainable with conventional digital twins.

2. THE ULTIMATE EVOLUTION OF DIGITAL TWINNING – THE WORLD AVATAR (TWA)

2.1 The architecture and implementation of TWA

The aspirational vision of TWA is to attain a comprehensive and generalisable knowledge representation that encapsulates the entirety of conceivable concepts, not confined to terrestrial entities. This expansive interpretation of the "world" in the context of TWA does not refer to planet Earth but encompasses all possible ideas and relationships [12, 18].

One means to realise the vision of TWA is to employ explicit knowledge models that are dynamically managed and enhanced by an autonomous system of semantic computational agents. These agents would operate in a closed-loop system, maintaining and enriching the knowledge base, thereby ensuring that the ultimate TWA's representation remains current, accurate, and reflective of the real-time dynamics of the systems [12, 18].

TWA is currently built using ontologies, KGs, and semantically aware computational agents. These technologies enable the semantic description and interlinking of both physical and digital components, establishing a unified knowledge base that amalgamates multi-domain data and functional computational agents. This provides a solution that allows facilitates seamless interoperability, fostering a connectedness that allows the sharing and utilisation of data and insights throughout the system. Ultimately, the architectural design of TWA is envisioned to serve as a prototype for a universal digital twin, with the capacity to propel digital twinning capabilities beyond the conventional scope of connected digital twins [18].

2.2 The core concepts of TWA

The core concepts in TWA are outlined below, providing a foundation for understanding its underlying core technologies. For a comprehensive exploration of these elements, readers are directed to the recent work [12].

The Semantic Web represents an extension of the World Wide Web, facilitating the sharing and reuse of data across diverse application domains. It employs standardised formats and protocols that enable machines to comprehend the semantics of data [19].

Ontologies serve as formal and explicit specifications of a set of concepts and their interrelations. Within the context of digital twins, ontologies offer a mechanism to uniformly represent data from disparate sources in a machine-readable format, which is essential for the effective integration of various systems [20].

KGs in TWA represent information in the form of nodes and edges. This enables the integration of complex, multi-domain data and allowing computational agents to interact with the data based on the relationships present. Meanwhile, 'dynamic KGs' are KGs within TWA that are continuously updated with new data, ensuring real-time relevance on the KGs.

Computational agents are software components within TWA that utilise semantic information from KGs to execute tasks including data ingestion, processing, and updating. They enable TWA to have dynamic behaviour and automate tasks (*i.e.*, maintaining, updating and analysing new data throughout the KG) [22].

3. CASE STUDIES OF TWA IN GERMAN

The case studies showcase how TWA effectively addresses real-world urban challenges, demonstrating its potential to drive sustainable city development.

3.1 District scale TWA implementation on Pirmasens-Kaiserslautern

Data silos are common in separate city-owned geographic information system (GIS) servers, *i.e.*, ALKIS parcels, OpenStreetMap, city-owned APIs, and even the German TABULA building archetypes. With TWA, the data are well integrated and with the help of semantically aware computational agents, TWA can provide valuable insights to users.

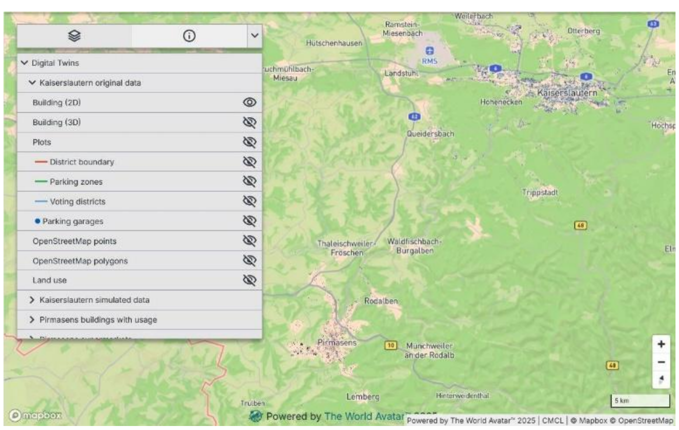

Fig 1. Integrated view of different data layers of the cities Kaiserslautern and Pirmasens.

Fig 1 presents a broad overview of the cities of Kaiserslautern and Pirmasens. TWA semantically integrates data describing 2D building footprints and vector meshes, car parks, voting districts, simulated energy demands *etc.*, providing a detailed representation of the urban landscape. Data are seamlessly sourced from OpenStreetMap, CityGML, ALKIS, energy certificates, and parking APIs. This integration creates a dynamic and self-updating description of the cities that reflects the latest information without manual intervention, ensuring the data remains current and useful for a variety of applications.

The unified framework provided by TWA can be invaluable for governmental agencies, enabling them to perform comparative analyses across different urban centres. This can inform decisions on infrastructure development and resource allocation. Similarly, industries operating within these cities can utilise the integrated view to optimise their operations, logistics, and supply chain management.

Potential future developments for TWA include the incorporation of dynamic EV-routing agents and integration with gen-AI. These enhancements could enable TWA to address even more complex queries efficiently, further solidifying its role as a robust decision-support tool and empowering stakeholders to tackle urban challenges with greater precision and adaptability.

3.2 Leveraging advanced urban data analytics to improve public infrastructure in Pirmasens

Pirmasens, a city in southwestern Germany, has been actively transforming its urban landscape to enhance community life. Its compact layout and mixed-use neighbourhoods provide an ideal setting for initiatives that boost commercial vitality, where success heavily depends on thoughtful urban planning.

Fig 2 offers a comprehensive view of Pirmasens' infrastructure through TWA, integrating 3D building models with isochrone data indicating walking distances to public toilets. This powerful tool can allow urban planners to filter and analyse specific data relevant to their planning needs. The isochrone visualisation, displayed in varying shades of green, reveals walking times to public toilets, with darker green representing short distances (5 minutes) and lighter green indicating intermediate distances (15 minutes), while grey areas signify larger distances. This detailed representation highlights two main concentration areas and identifies zones within the city that currently lack convenient access to public toilets.

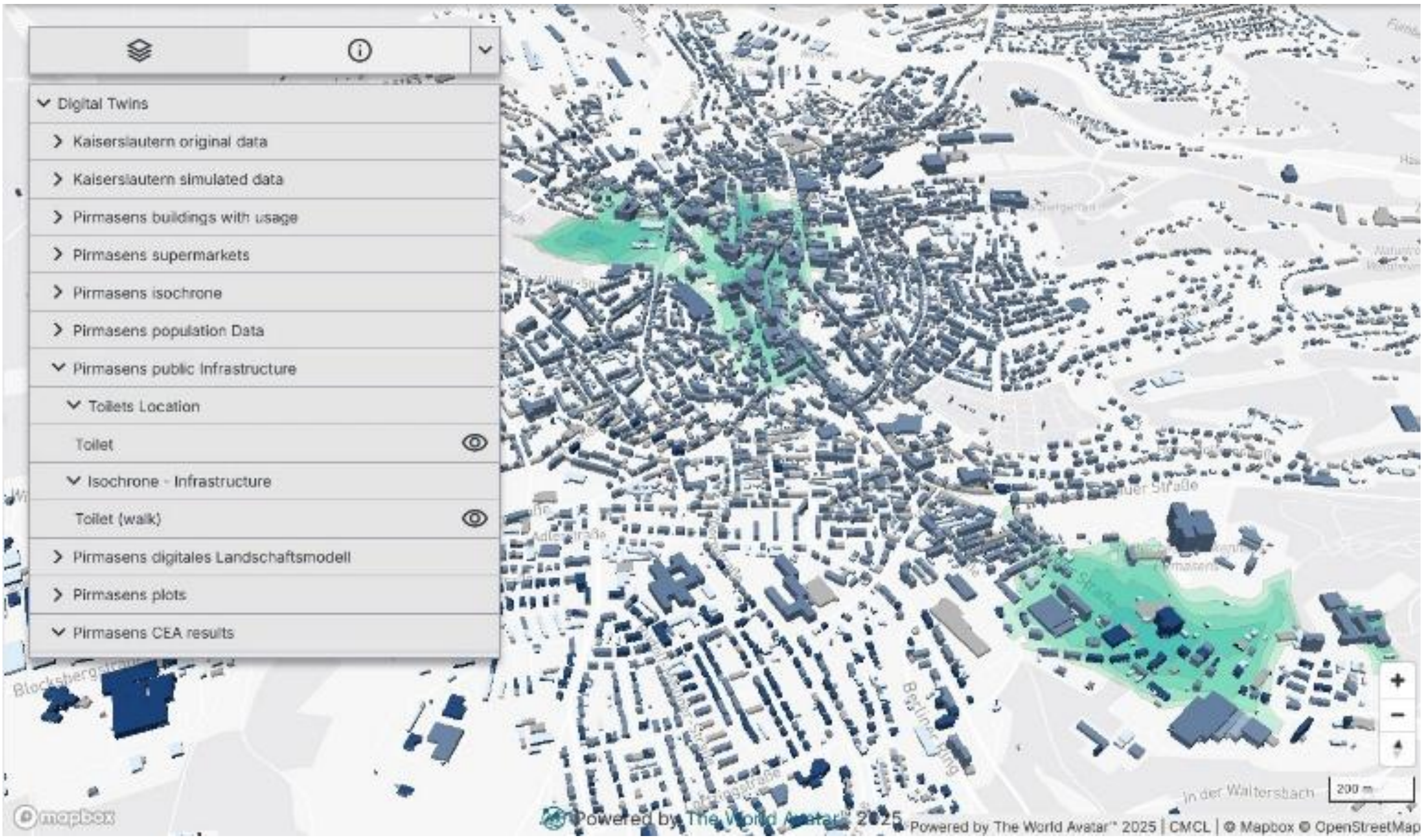

Fig 2. Isochrone data indicating walking distances to public toilets in the city of Pirmasens.

By analysing this data, local authorities can strategically enhance infrastructure, improve coverage, and create pedestrian-friendly routes to improve accessibility to public facilities. The integration of 3D building models and terrain data offers a comprehensive view of the urban landscape, which can aid in assessing connections between public amenities and surrounding landmarks. This use case exemplifies how TWA can potentially help urban planners to leverage data-driven approaches to optimise infrastructure, ensuring that new developments consider accessibility and that existing facilities better serve residents and visitors alike.

3.3 Bremen in 3-D: Where buildings meet heat, milieu and land-use

Bremen, a port city in northwest Germany, presents a complex urban tapestry of industrial history and modern urban dynamics. Its diverse building stock and varied land uses create a multifaceted energy demand, which is further complicated by climate change. In this use case, TWA attempts to tackle and dissect these complex challenges by integrating energy data on heating demand, building characteristics, and topography. With this integration, it is hoped to provide insights to achieve sustainable urban planning and execution within the city through TWA.

Fig 3. Visible heating demand, visible milieu, visible land use of the city Bremen to provide insights to assess energy efficiency of buildings.

Fig 3 presents a detailed visualisation of Bremen, showing the application of TWA in urban energy planning. The 3D model integrates data that provide a comprehensive view of the city's energy landscape. The colour gradient from warm to cool represents the annual heating demand per square meter of gross floor area, as calculated by the City Energy Analyst tool [23]. Analysis shows that the buildings with high heating demand are concentrated within the same area. This provides a clear indication that improvements in optimising or improving heating supply will have to be based on these clusters to ensure maximum impact within the city. This integrated information can also be crucial for urban planners and policymakers in assessing which areas require the most urgent energy efficiency improvements.

3.4 Energy efficiency and renewable potential in Oberhausen's commercial area

Oberhausen, located in the Ruhr Metropolitan region of North Rhine-Westphalia, Germany, has a historical foundation rooted in coal mining and steel production. However, the decline of the coal and steel industries in the 1960s led to economic and demographic challenges, including urban shrinkage and high unemployment rates. Hence, Oberhausen has been actively pursuing strategies for urban regeneration and transformation toward a more sustainable economy. This context makes Oberhausen an exemplary case study for applying TWA to optimise energy efficiency and promote renewable energy integration within its commercial and residential sectors.

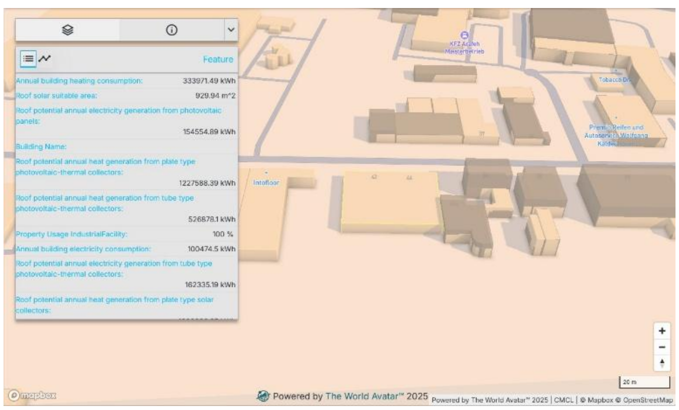

Fig 4. Heat consumption and electricity generation of buildings in the city of Oberhausen.

Fig 4 provides a detailed snapshot of a commercial area in Oberhausen, showcasing the capabilities of TWA in analysing the heat and electric aspects of buildings. The selected building, highlighted in the visualisation, serves as a focal point for demonstrating the ability of TWA to assess energy consumption and potential generation from renewable sources. The data presented includes the annual building heating consumption, which stands at 333,971 kWh, indicating the heat energy demand of the building. Additionally, the roof solar suitable area is quantified at 930 m², suggesting the potential for solar energy harnessing for the building.

Furthermore, the figure reveals the roof's potential for annual electricity generation from photovoltaic panels, estimated at 154,555 kWh, and the potential heat generation from both plate and tube type photovoltaic-thermal collectors, at 1,227,588 kWh and 526,878 kWh respectively. This figure shows the significant potential for on-site renewable energy generation, which could substantially offset the electricity consumption of the building (100,475 kWh) and contribute to reducing its reliance on non-renewable energy sources. The analysis of such data is crucial for urban planners and energy managers in optimising energy use and promoting sustainability within commercial districts. The integrated approach of TWA can enable a nuanced understanding of the energy profile of each building, potentially facilitating targeted interventions and improvements in energy efficiency and renewable energy integration within a city. With the integration of gen-AI, it could be expanded to include personalised suggestions for building owners too.

4. CONCLUSIONS

This paper has demonstrated the potential of TWA as a transformative tool in sustainable urban development. Particularly, TWA leveraged semantic technologies to transcend the limitations of traditional digital twins, addressing the issue of interoperability faced in traditional digital twins. The case studies presented have illustrated the unique propositions of TWA, enabling seamless human-machine interactions with diverse data sources, which is crucial for addressing urban challenges (*i.e.*, resilience, infrastructure planning, and decarbonisation).

The application of TWA in German cities has provided tangible evidence of its potential to facilitate sustainable and data-driven solutions, thereby enhancing the flexibility, resilience, and intelligence of urban infrastructure. The ability of TWA to integrate multiple data streams and support real-time decision-making has been highlighted as critical for generating comprehensive insights into urban sustainability and infrastructure development.

TWA's approach to data integration, analysis, and the inclusion of a broad spectrum of concepts and world knowledge marks a significant advancement over conventional digital twinning. TWA can offer urban planners and policymakers powerful means for potentially creating more resilient, intelligent, flexible, and sustainable systems for urban environments and management. As cities continue to grapple with the complexities of urbanisation and the imperatives of sustainable development, TWA stands as a promising solution that aligns with global sustainability goals and supports the evolution towards smarter cities.

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DATA AVAILABILITY

The World Avatar source code can be found at https://github.com/TheWorldAvatar

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