reviewed paper

3D City Models as Simulation Infrastructure: Open Tools, Proprietary Gaps and Application Scenarios in Everyday Planning

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1 ABSTRACT

Digital Twins are increasingly used as analytical frameworks in urban planning, supporting spatially explicit assessments of climate, energy and environmental risks. Based on interoperable 3D city models (e.g. CityGML/CityJSON) and shared geodata infrastructures, they enable scenario-based evaluations across multiple planning domains. This paper examines how Digital Twin workflows can support planning-oriented simulation tasks, with a particular focus on the interplay between open-source and proprietary tools.

Using the city of Landsberg am Lech as an applied case study, four thematic applications are investigated: solar framework planning in a protected historic ensemble, urban heat screening, pluvial flood risk assessment, and environmental noise scenarios. The workflows combine open data – most notably LOD2 building models and digital terrain models – with a hybrid toolchain including QGIS, GRASS GIS, Honeybee, ICETools, H-Risk, as well as proprietary environments such as Rhino/Grasshopper and ArcGIS Pro.

The results demonstrate that Digital Twins function most effectively as shared spatial reference systems for planning-oriented screening and orientation analyses, rather than as fully integrated simulation platforms. While physically based models such as PALM-4U represent the state of the art in urban climate modelling, simplified tools proved suitable for early-stage planning and comparative scenario evaluation. Overall, the study shows that hybrid workflows combining open and proprietary tools currently represent best practice, balancing transparency, methodological robustness, and planning relevance.

Keywords: Digital Twin, Open-Source Planning Tools, Hybrid Simulation Workflows, Noise, Urban Climate Simulation

2 INTRODUCTION

Contemporary urban planning is increasingly challenged by a set of highly complex, mutually dependent issues related to climate change, efficient resource use, and risk governance. Heat stress, pluvial flooding, noise exposure, and energy transition processes interact spatially and temporally, often exceeding the analytical capacity of traditional two-dimensional planning instruments. In this context, digital technologies have become central to contemporary planning practice. While the concept of the Smart City has primarily been associated with sensor-based, real-time optimisation and proprietary platforms (BATTY, 2018, p. 2; GRIEVES, 2014), the notion of the Open Digital Twin (DEMBSKI et al., 2020; KETZLER et al., 2020) emphasises a different paradigm: the creation of interoperable, transparent, and reproducible digital representations of urban space based on open standards and open data.

Open Digital Twins are not primarily visualisation tools but analytical infrastructures (ZIEHL et al., 2023). They integrate 3D city models, geospatial datasets, and simulation environments to support scenario-based planning, early-stage decision-making, and interdisciplinary collaboration. Their growing relevance is closely linked to the increasing availability of open geodata, such as Level of Detail 2 (LOD2) building models, digital terrain models (DTM), and open-source geographic information systems.

This paper investigates the role of Open Digital Twins in urban planning with a specific focus on climate-related applications. It addresses two central research questions:

- Which planning-relevant simulations can already be conducted entirely with open-source tools?
- In which areas do proprietary software solutions remain necessary due to regulatory, methodological, or institutional constraints?

Using the city of Landsberg am Lech as a case study, the paper demonstrates how a hybrid toolchain combining open-source and proprietary software can be implemented in practice. The contribution aims to provide both a conceptual framework and empirical insights for planners, municipalities, and researchers working with digital urban models.

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3 STATE OF THE ART: SIMULATION-BASED URBAN PLANNING WITH DIGITAL TWINS

3.1 3D City Models as Analytical Infrastructure

The application of digital twins in urban planning has expanded significantly over the last decade, driven by advances in geospatial data availability, 3D city modelling, and simulation technologies. Rather than constituting a single methodological approach, digital twins increasingly function as integrative frameworks that support multiple thematic analyses (JEDDOUB et al., 2023). In current research and planning practice, four application domains are particularly prominent: solar energy assessment, urban climate modelling, hydrological risk analysis, and environmental noise evaluation (ZHU & JIN, 2025).

3.2 Solar Potential Analysis and Urban Solar Frameworks

Solar potential analysis represents one of the most mature and widely applied use cases of 3D city models in urban planning. The availability of LOD2 building data enables the calculation of roof orientation, inclination, shading effects, and annual solar irradiation with high spatial resolution. Numerous studies demonstrate that solar cadastre systems based on 3D city models provide reliable decision support for municipal energy strategies (BROSCHART et al., 2024).

Recent research increasingly emphasises strategic, city-wide solar planning beyond parcel-based assessments. Solar framework plans (Solarrahmenpläne) translate technical potential analyses into spatially differentiated planning instruments that integrate urban morphology, heritage protection, densification strategies, and policy objectives (ZEILE et al., 2025).

Methodologically, these approaches rely on reproducible GIS-based workflows. While open-source tools support transparent modelling of solar radiation and scenario comparison (ROUDSARI et al., 2013), proprietary software remains relevant for detailed economic or grid-related assessments. The solar framework plan presented at REAL CORP 2025 (ZEILE et al., 2025) illustrates how Digital Twins can serve as spatial decision-support systems that link energy analysis and urban planning.

3.3 Urban Climate and Heat Stress Modelling

Urban climate modelling has become increasingly important due to rising heat stress and the need for climate adaptation. Digital twins support this domain by providing detailed representations of urban form, which strongly influence radiation balance, airflow, and thermal comfort (LOPEZ-CABEZA et al., 2025).

Current approaches range from simplified surface-based models to entirely physical, three-dimensional atmospheric simulations. Open-source tools such as Ladybug/Honeybee enable accessible, iterative assessments of solar exposure and shading, while the PALM-4U model system represents a state-of-the-art, physically based approach to urban climate simulation (BAKLANOV et al., 2020; HELDENS et al., 2020).

Proprietary tools such as ENVI-met remain widely used for detailed microclimatic studies (BRUSE, 2000), although recent literature highlights the suitability of simplified models for planning-oriented, comparative analyses.

3.4 Pluvial Flooding and Surface Runoff Analysis

Hydrological risk analysis, particularly pluvial flooding, has become increasingly relevant in urban planning due to the rising frequency of extreme rainfall events. Digital twins enable the integration of terrain models, surface characteristics, and built structures to analyse runoff pathways and accumulation zones.

Open-source GIS environments such as GRASS GIS and QGIS provide robust tools for surface runoff analysis (SCHNEIDER, 2025; "SplashTool"). These methods support transparent, reproducible modelling and are widely applied in municipal risk mapping and climate adaptation planning. Proprietary platforms such as ArcGIS Pro offer extended functionalities and are often embedded in administrative workflows, while the underlying modelling principles remain transferable across software environments.

3.5 Environmental Noise Modelling

Environmental noise assessment constitutes an established application of digital spatial models. Noise exposure is strongly influenced by building geometry, street layout, and traffic volumes, making 3D city models particularly suitable for spatially differentiated analysis.

Recent developments in open-source GIS plugins, such as H-Risk (TAGUSARI, 2024), demonstrate that scenario-based noise modelling can support early planning stages by enabling relative comparisons of urban form, traffic management, and mitigation measures. For legally binding noise assessments, proprietary software remains dominant; however, the literature increasingly acknowledges simplified tools as complementary instruments in planning practice.

3.6 Synthesis

Across all four domains, the literature indicates a convergence towards scenario-based planning workflows supported by Digital Twins. While thematic priorities differ, shared methodological requirements – interoperable data models, reproducible simulations, and spatial transparency – are evident. Solar framework planning emerges as a particularly effective interface between technical simulation and strategic urban planning, highlighting the broader potential of Digital Twins as decision-support systems.

4 LANDSBERG AM LECH TEST-SITE

4.1 The (Open) Digital Twin of Landsberg am Lech

The city of Landsberg am Lech serves as a case study demonstrating how Open Digital Twin workflows can be implemented in municipal planning practice. As a medium-sized city with accessible open geodata, a heterogeneous building stock, and increasing challenges related to climate adaptation and energy transition, Landsberg am Lech represents a typical and transferable European planning context.

The digital twin used in this study follows a planning-oriented interpretation of the Digital Twin concept, as discussed in recent contributions (BROSCHART et al., 2025). Rather than aiming at real-time monitoring or sensor-driven control, the model focuses on spatial analysis, scenario development, and decision support for strategic and early-stage planning processes, aligning with research that positions urban digital twins as integrative spatial frameworks rather than purely operational systems.

The data basis consists primarily of open and municipal datasets, including a Level of Detail 2 (LOD2) building model, a high-resolution digital terrain model (DTM), land use information, and thematic layers related to vegetation, mobility infrastructure, and environmental constraints. These datasets were harmonised within a GIS environment using interoperable data models, enabling consistent use across multiple analytical domains.

Crucially, the digital twin is not conceived as a monolithic model but as a shared spatial reference system connecting different simulation tools and thematic analyses. In this sense, the model represents a planning-oriented digital twin, designed to support scenario-based analysis, comparative evaluation, and interdisciplinary workflows. This structure allows diverse planning questions – such as solar energy potential, urban heat mitigation, surface runoff, and noise exposure – to be addressed using a common geometric and semantic foundation while retaining methodological flexibility.

By emphasising openness, reproducibility, and thematic integration, the Landsberg am Lech Digital Twin demonstrates how municipalities can operationalise digital twins as practical planning instruments that support both technical analysis and strategic discourse.

4.2 Solar Framework Planning using the Digital Twin

Solar energy assessment constitutes a particularly relevant application of Digital Twins in historic urban contexts, where technical potential alone is insufficient as a planning criterion. In Landsberg am Lech, the Digital Twin was applied to develop a solar framework plan (Solarrahmenplan) explicitly addressing the challenges of solar energy deployment within a protected historic ensemble. The central planning question was not whether solar energy is technically feasible, but which types of solar installations are compatible with heritage protection requirements and urban visual integrity.

4.2.1 Planning Context: Solar Energy in Historic Ensembles

The historic core of Landsberg am Lech is characterised by a dense building fabric, heterogeneous roof typologies, and strict heritage protection regulations. In such contexts, conventional solar cadastres reach their limits because they typically identify technically suitable roof surfaces without accounting for visual exposure, material compatibility, or monument-preservation objectives.

The solar framework plan, therefore, reframes solar potential analysis as a spatial governance instrument. Its purpose is to support differentiated planning decisions by identifying zones where solar installations are permissible, conditionally acceptable, or to be avoided, and by distinguishing between different photovoltaic and solar thermal technologies. This approach follows the logic presented in recent CORP research (ZEILE et al., 2025), positioning solar framework planning as an interface between energy transition and urban heritage management.

4.2.2 Digital Twin as Analytical and Visual Reference

Solar irradiation analysis was used as a supporting layer within the framework plan, but did not constitute its primary decision criterion. Instead, irradiation values were interpreted in combination with roof typologies, visibility conditions, and conservation guidelines. This enabled the classification of roof surfaces into differentiated categories, such as suitable for non-visible installations, ideal for visually integrated systems, or unsuitable due to heritage sensitivity.

The analytical workflow combined GIS-based processing with parametric modelling environments. While open-source tools were used to prepare and structure the LOD2 data, subsequent analyses and visual evaluations were conducted in commercial software environments, including Rhino/Grasshopper and ArcGIS Pro (Fig. 1). This hybrid setup reflects planning practice, in which analytical requirements rather than licensing models guide tool selection.

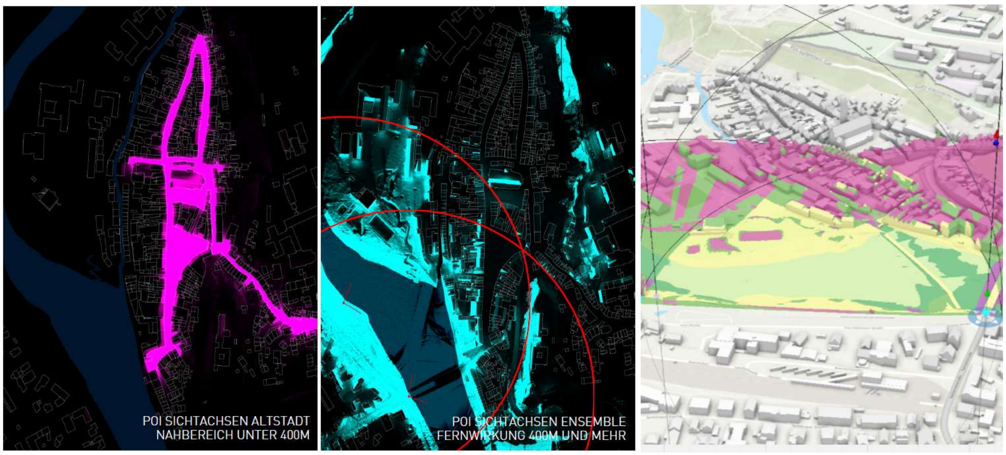

Fig. 1: Various approaches to visibility analysis using Rhino and ArcGISPro (left& middle: Herm & Benkeser 2025, right: own source)

4.2.3 Modelling Solar Suitability under Heritage Constraints

Solar irradiation analysis was used as a supporting layer within the framework plan, but did not constitute its primary decision criterion. Instead, irradiation values were interpreted in combination with roof typologies, visibility conditions, and conservation guidelines. This allowed the classification of roof surfaces into differentiated categories, such as suitable for non-visible installations, ideal for visually integrated systems, or unsuitable due to heritage sensitivity.

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4.2.4 Differentiation of Solar Technologies

A key contribution of the solar framework plan lies in its explicit differentiation among solar technologies. Rather than treating photovoltaic systems as a homogeneous category, the framework distinguishes between conventional PV modules, building-integrated photovoltaics (BIPV), solar tiles, and solar thermal systems. Each technology exhibits distinct visual characteristics and degrees of compatibility with historic roofscapes.

By linking technology categories to spatial zones within the Digital Twin, the solar framework plan provides concrete guidance for planners, heritage authorities, and property owners. In this role, the Digital Twin acts as a mediating instrument, translating abstract conservation principles into spatially explicit planning recommendations.

4.2.5 Planning Relevance and Strategic Value

The Landsberg am Lech solar framework plan demonstrates how Digital Twins can support nuanced planning decisions in sensitive urban contexts. Rather than maximising energy yield, the framework prioritises contextual appropriateness and visual integration, thereby reducing the potential for conflict between energy policy and heritage protection.

Importantly, the Digital Twin does not replace detailed architectural design or approval procedures. Instead, it provides strategic orientation at an early stage, supports transparent communication among stakeholders, and increases planning certainty.

4.3 Urban Heat and Microclimate Assessment

Urban heat stress represents a critical challenge for cities, particularly in dense urban areas with limited vegetation and high surface sealing. Within Open Digital Twin workflows, microclimate assessment functions as an essential analytical layer for evaluating the spatial effects of urban form, materiality, and vegetation on thermal comfort. In the Landsberg am Lech case study, urban heat assessment was implemented as a planning-oriented screening and orientation tool, rather than as an entirely physical climate simulation.

4.3.1 Reference Framework: Physically Based Urban Climate Models

From a scientific perspective, physically based urban climate models such as PALM-4U represent the state of the art in microclimate simulation. PALM-4U enables high-resolution modelling of air temperature, radiant heat fluxes, airflow, vegetation–atmosphere interactions, and human thermal comfort, and its integration into Digital Twin environments is increasingly discussed in research and municipal climate adaptation studies (BENDER et al., 2023).

However, despite its methodological advantages, PALM-4U requires substantial computational resources, specialised expertise, and extended setup times. In the Landsberg am Lech case study, PALM-4U served as a conceptual reference model but was not applied operationally. Instead, simplified and more accessible approaches were selected to support exploratory planning questions.

4.3.2 Applied Tools: Honeybee and ICETools

Urban heat assessment in Landsberg am Lech was conducted using a combination of Honeybee (Grasshopper/Rhino) and ICETools (QGIS). These tools were selected to balance analytical relevance with practical feasibility in a planning context, as demonstrated in accompanying academic exercises.

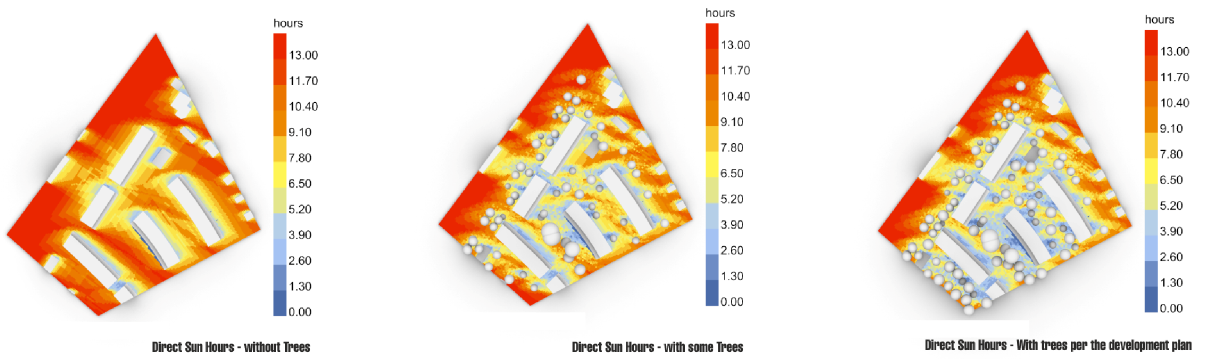

Fig. 2: Heat development in the xy new development area in Landsberg with varying vegetation densities, simulated in Heneybee. The areas with reduced heat stress due to vegetation are clearly visible. (Flores & Zumholte 2025)

Honeybee was used to analyse solar radiation exposure, shading patterns, and surface-related thermal indicators using the LOD2 building model and selected scenarios. Its parametric structure supports rapid iteration and comparison of spatial configurations, particularly regarding vegetation placement and building geometry. While Honeybee does not simulate atmospheric dynamics, it provides valuable insights into radiation-driven heat loads (see Fig.2).

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ICETools was used as a complementary method to estimate surface temperature patterns based on simplified energy balance calculations. By integrating land cover, vegetation, and shading information, ICETools enables reproducible, low-threshold heat assessments that are well-suited for early-stage planning and scenario comparison.

4.3.3 Methodological Limitations of Tool Integration

Despite increasing tool availability, the integration of urban climate simulations into Digital Twin workflows remains methodologically fragmented. Tools such as ICETools and ENVI-met require substantial model reconstruction, as existing Digital Twin geometries cannot be used seamlessly. Buildings, vegetation, surface materials, and boundary conditions must be newly parameterised within each simulation environment, limiting reproducibility and increasing modelling effort.

Parametric environments such as Honeybee offer greater interoperability, as 3D city models can be imported directly. However, practical experience shows that combining LOD2 building geometries with digital terrain models (DTMs) poses significant challenges. At building–terrain interfaces, geometric inconsistencies may occur, leading to artefacts such as implausible surface temperature anomalies (“cold spots”).

These issues are primarily caused by geometric and semantic mismatches between datasets generated for different purposes. Without careful preprocessing and validation, such inconsistencies can propagate into simulation results. Consequently, current Digital Twin workflows should be understood as loosely coupled toolchains, reinforcing the need for staged modelling approaches in which simplified tools support early decision-making and more complex models are applied selectively.

4.4 Pluvial Flood Risk and Surface Runoff

Pluvial flooding constitutes a recurring challenge in urban planning, particularly in compact settlement structures with high degrees of surface sealing. In the case of Landsberg am Lech, surface runoff analysis was implemented as a planning-oriented screening tool to rapidly identify spatial patterns, flow paths, and potential accumulation zones relevant to urban development and climate adaptation.

4.4.1 Data Basis and Digital Twin Integration

The analysis was based on a Digital Terrain Model (DTM) and the LOD2 building model, both of which could be directly integrated into the Digital Twin environment. The DTM provided the basis for modelling surface gradients and runoff directions, while LOD2 buildings served as physical obstacles that influenced flow paths and accumulation areas.

A key advantage of this approach is the flexibility in data preparation. Terrain data can be rapidly adjusted using grayscale heightmaps, enabling quick testing of alternative surface conditions or simplified scenarios. This allows planners to explore assumptions about surface sealing, microtopography, or redevelopment with minimal preprocessing effort, while ensuring consistent representation of terrain and built structures.

4.4.2 Modelling Approach and Tools

Surface runoff modelling was conducted using QGIS Splash Tools and ArcGIS Pro flow path analysis, both of which support direct use of terrain and building data without complex model reconstruction. The tools calculate flow directions and accumulation zones based on terrain gradients and produce visually intuitive results.

The modelling approach focuses on relative flow behaviour, highlighting areas where water is likely to concentrate during intense rainfall events. Rather than simulating exact water depths or temporal dynamics, the analysis identifies structural vulnerabilities in the urban fabric. While terrain and building data can be ingested directly, the modelling process remains loosely coupled to the Digital Twin and requires tool-specific parameterisation.

4.4.3 Visualisation and Interpretability

A central strength of the applied method is the visual clarity of the results. Flow paths, accumulation areas, and potential impact zones can be visualised directly within the Digital Twin, supporting intuitive interpretation by planners and non-technical stakeholders. As both tools operate on raster-based height models, results can be rapidly updated, enabling iterative scenario evaluation.

The pluvial flood analysis is explicitly coarse and exploratory. It does not account for underground drainage systems, sewer capacities, or time-dependent rainfall scenarios. Accordingly, results are interpreted as orientation maps for planning, not as regulatory flood hazard maps. Embedded within the Digital Twin, the analysis supports prioritisation and complements other thematic assessments in a holistic planning context.

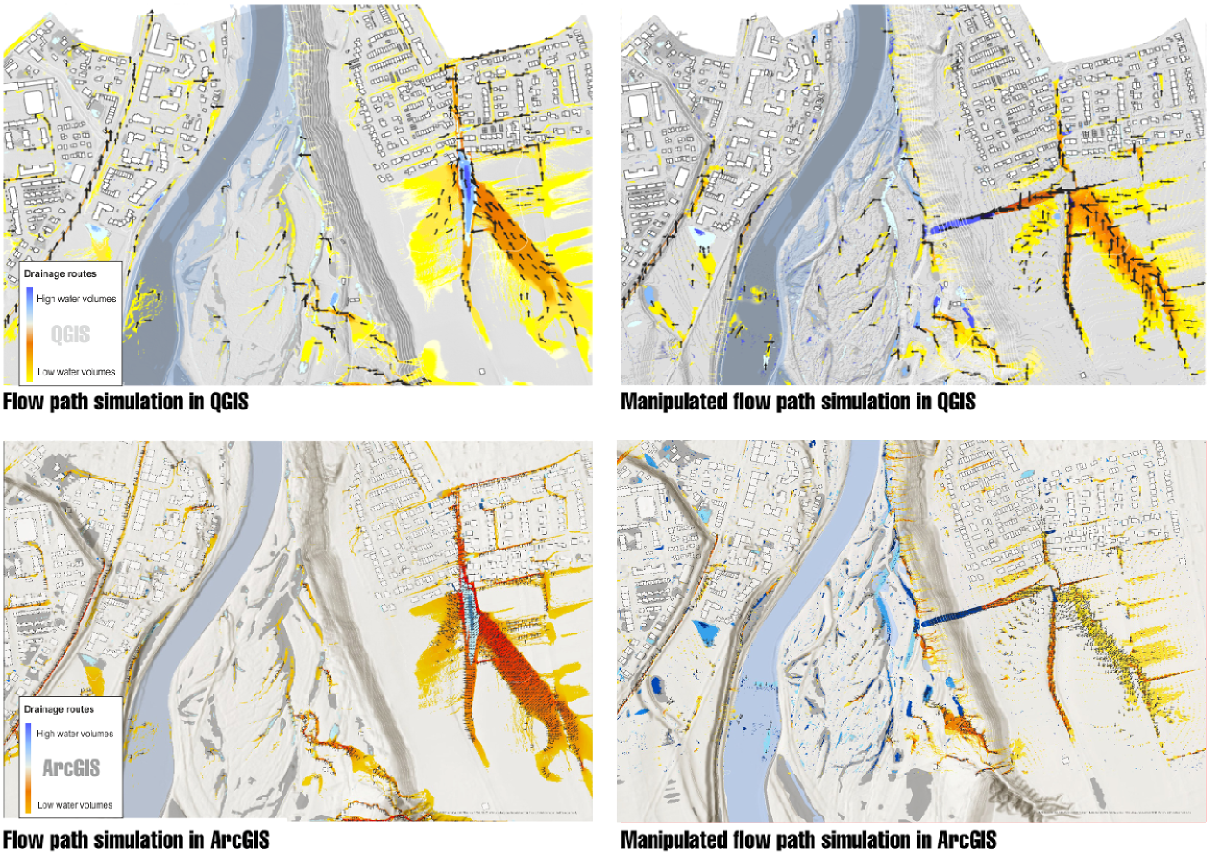

Fig.3: Comparison of the stream path simulation in QGIS and ArcGIS in the inventory (left side) and diverted water flow through terrain adaptation on the right (Kappeler & Schwarz 2025)

4.4.4 Planning Relevance and Limitations

The pluvial flood analysis conducted for Landsberg am Lech is explicitly coarse and exploratory. It does not account for underground drainage systems, sewer capacities, or time-dependent rainfall scenarios. Nevertheless, its value lies in its ability to quickly identify potential problem areas and support strategic planning discussions.

In line with the approach presented here, the results are interpreted as orientation maps for planning rather than regulatory flood hazard maps. They provide a robust basis for prioritising areas where further, more detailed hydrological or engineering analyses may be required. Embedded within the Digital Twin, the pluvial flood assessment complements other thematic analyses and contributes to a holistic understanding of spatial vulnerability in urban planning.

4.5 Environmental Noise Scenarios

Environmental noise represents an established but methodologically demanding field within urban planning. While norm-based proprietary software solutions often dominate noise assessment, recent work demonstrates that planning-oriented noise scenarios can also be explored within Digital Twin environments using simplified, transparent approaches. In the Landsberg am Lech case study, environmental noise modelling was therefore included as a supplementary analytical layer, in accordance with established methodological principles.

4.5.1 Planning-Oriented Noise Assessment

From a planning perspective, early-stage noise assessment focuses less on legally binding exposure values and more on relative spatial patterns. Key questions include the location of noise-sensitive uses, the influence of urban form on sound propagation, and the potential effects of alternative planning scenarios. Digital Twins provide a suitable spatial framework for addressing these questions, as building geometry, street networks, and land use are already integrated.

4.5.2 Applied Tools and Workflow

In Landsberg am Lech, noise scenarios were explored using H-Risk in QGIS, integrating open street data, traffic assumptions, and building geometries. The LOD2 building model served as the geometric basis for modelling reflecting and shielding effects, while OpenStreetMap (OSM) road network data provided the source structure for noise emission modelling (Fig. 4).

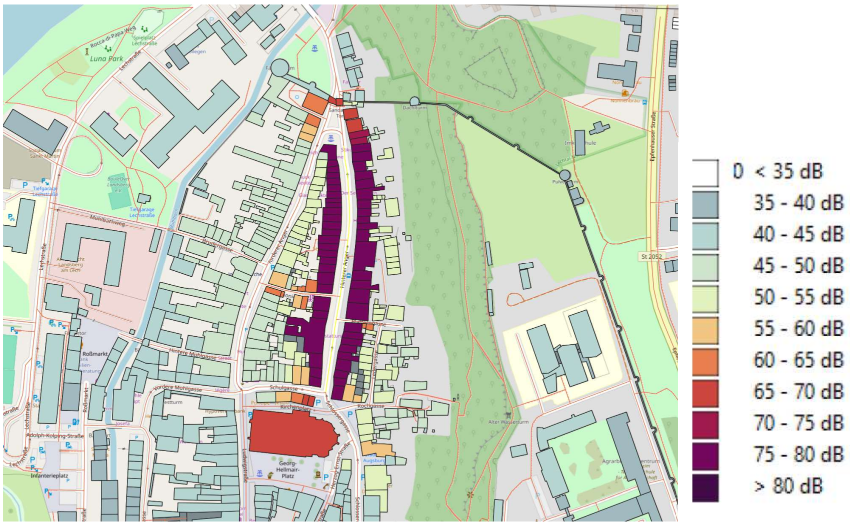

Fig. 4: Noise level at the facade 30km/h in QGIS/H-Risk (Strifler & Daum, 2025)

The workflow follows a simplified approach: traffic volumes and speed assumptions are parameterised, and resulting noise levels are calculated and visualised as spatial distributions. This enables rapid comparison of alternative scenarios, such as changes in traffic routing or street hierarchy. The Digital Twin ensures spatial consistency with other thematic analyses, while the noise analysis itself operates on a tool-specific abstraction rather than a fully integrated twin model.

4.5.3 Interpretation and Limitations

The applied noise modelling approach is explicitly non-normative. It does not replace standardised noise mapping procedures required for regulatory compliance. Still, it serves as a planning-oriented screening and orientation tool, highlighting areas where noise exposure may become critical under certain assumptions. Such simplified models are particularly valuable in early planning stages, where they support spatial awareness and informed discussion rather than final verification. For legally binding assessments, proprietary tools such as CadnaA or SoundPLAN remain necessary.

5 CONCLUSIONS, SYNTHESIS AND OUTLOOK

Taken together, the four applied use cases illustrate that the Digital Twin of Landsberg am Lech functions less as a fully integrated simulation environment and more as a shared spatial reference for planning-oriented screening analyses. This hybrid use of open and proprietary tools forms the basis for the comparative synthesis presented in this chapter.

5.1 Synthesis of Findings

This paper explores how Open Digital Twin workflows can support simulation-based urban planning, using Landsberg am Lech as a case study. Across the four thematic domains – solar framework planning, urban heat assessment, pluvial flooding, and environmental noise – the results demonstrate that the Digital Twin functions most effectively as a shared spatial reference system, rather than as a fully integrated simulation environment. The applied examples confirm that Digital Twins are particularly valuable for planning-oriented screening and orientation analyses. Their primary contribution lies not in predictive accuracy or regulatory compliance but in structuring complex spatial questions, enabling scenario comparison, and supporting interdisciplinary communication. This finding aligns with recent research that positions urban digital twins as integrative planning infrastructure rather than operational control systems.

A central insight from the Landsberg am Lech case is that thematic simulations do not require monolithic or fully synchronised models. Instead, loosely coupled workflows, anchored in a consistent geometric and semantic base, allow planners to address different questions with appropriate tools.

5.2 Open-Source and Proprietary Tools: A Comparative Perspective

A key objective of this study was to assess the role of open-source and proprietary software within Digital Twin workflows. The results indicate that tool choice is primarily driven by planning objectives and methodological requirements, rather than by licensing models.

Open-source tools play a crucial role in early-stage planning and exploratory analysis by supporting transparency, reproducibility, and rapid iteration. Proprietary tools remain relevant where standardised procedures, normative requirements, or advanced physical modelling are required. Table 1 summarises the complementary roles of both tool categories across the four thematic domains.

Planning Domain	Open-Source / Accessible Tools	Proprietary Tools	Role within the Digital Twin
Solar Planning	QGIS, GRASS GIS, parametric modelling (data preparation)	Rhino/Grasshopper, ArcGIS Pro	Strategic spatial differentiation (Solar Framework Plan)
Urban Heat	Honeybee, ICETools	ENVI-met, PALM-4U (reference)	Screening and comparative scenario analysis
Pluvial Flooding	QGIS Splash Tools, GRASS GIS	ArcGIS Pro	Identification of flow paths and accumulation zones
Environmental Noise	H-Risk (QGIS)	CadnaA, SoundPLAN	Orientation and scenario comparison

Table 1: Open-Source and Proprietary Tools in Planning-Oriented Digital Twin Workflows

Rather than competing alternatives, open-source and proprietary tools form complementary components of hybrid workflows, with open data – particularly LOD2 buildings and terrain models – providing the stable foundation for both.

5.3 Methodological Implications for Digital Twin Use

The applied workflows highlight several methodological implications. First, full integration of simulation tools into a single Digital Twin environment remains limited, as climate, hydrological, and noise models typically require tool-specific abstractions of geometry and attributes.

Second, geometric and semantic mismatches – particularly at building–terrain interfaces – represent a persistent challenge across simulation domains. Acknowledging these limitations is essential to avoid overinterpretation and to maintain methodological transparency.

Third, a staged modelling approach emerges as a pragmatic strategy: lightweight, planning-oriented tools support early decision-making, while advanced, physically based models can be applied selectively when higher accuracy or regulatory compliance is required.

5.4 Outlook

Future developments in semantic data modelling, improved terrain–building integration, and the maturation of open-source simulation frameworks such as PALM-4U may reduce current interoperability barriers. At the same time, institutional learning and capacity building will be critical for responsible and effective Digital Twin use. Rather than striving for fully integrated, all-encompassing platforms, planning practice may benefit more from robust, modular Digital Twins that support thematic extension and methodological flexibility. The Landsberg am Lech case demonstrates that such an approach is already feasible and can meaningfully contribute to climate-responsive, context-sensitive urban planning.

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