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D.1.4.3 Transnational protocol for neighbourhood digital twin development

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DIGITALIZATION OF SCANNED NEIGHBOURHOODS

A. INTRODUCTION

1.1. Purpose of the Protocol

This document defines a transnational protocol for the development of neighbourhood digital twins within the ZEB4ZEN project. The purpose of the protocol is to:

- establish a harmonized methodological framework for digital twin creation across all pilot cities
- ensure consistency, comparability, and interoperability of datasets and modelling approaches
- support the integration of digital twins into energy planning and decision-making processes
- enable replication and scalability of the methodology to other historical urban areas

The protocol builds upon prior project outputs, particularly:

- the methodology for digitalization and GIS-based modelling
- the data structure and functional requirements of the VR-based digital twin platform

By combining these elements, the protocol ensures that digital twin development is not only technically robust but also aligned with the broader goals of achieving Zero-Emission Neighbourhoods (ZEN).

1.2. Scope and Application

The protocol applies to:

- ✓ all pilot cities within the ZEB4ZEN project
- ✓ future cities seeking to develop neighbourhood-scale digital twins
- ✓ stakeholders involved in urban energy planning, including:
- ✓ local authorities
- ✓ planners and engineers
- ✓ research institutions
- ✓ technology providers

The protocol covers the full lifecycle of digital twin development, including:

- ✓ data collection and structuring
- ✓ spatial integration and modelling
- ✓ dataset standardization
- ✓ scenario simulation and KPI calculation
- ✓ visualization and decision-support integration

The approach is designed to support both:

- ✓ baseline digital twin development (representation of current conditions)
- ✓ scenario-based digital twins (simulation of EE/RES measures and future pathways)

1.3. Relationship to Other Deliverables

This protocol is strongly aligned with and extends the following deliverables:

D1.4.2 – Digitalization of scanned neighbourhoods

Provides:

- ✓ practical methodology for data collection, structuring, and GIS integration
- ✓ procedures for aggregation at building and block levels
- ✓ calculation of energy and environmental KPIs

In this protocol, these elements are generalized, standardized, and harmonized across all partners.

D4.2.1 – Virtual Reality Tool Design

Provides:

- ✓ definition of input datasets and data structures
- ✓ requirements for data compatibility and interoperability
- ✓ integration of multicriteria decision-making and scenario evaluation

In this protocol, these elements are translated into data standards and requirements and embedded into a consistent transnational workflow.

1.4. Key Concepts

To ensure a common understanding across all partners, the following concepts are defined:

DIGITAL TWIN (NEIGHBOURHOOD LEVEL)

A digital representation of a neighbourhood integrating:

- ✓ spatial data (GIS, 3D models, point clouds)
- ✓ building-level attributes
- ✓ energy and environmental data
- ✓ scenario simulations and future projections

The digital twin serves as an analytical model and a decision-support environment.

BUILDING-LEVEL vs. BLOCK-LEVEL MODELLING

- ➢ Building level: detailed representation of individual structures
- ➢ Block level: aggregation for planning and scenario analysis

Aggregation from building to block level is essential for:

- ✓ KPI calculation
- ✓ scenario comparison
- ✓ strategic planning

SCENARIO-BASED DIGITAL TWIN

A digital twin that allows simulation of:

- ✓ energy efficiency measures (EE)
- ✓ renewable energy integration (RES)
- ✓ long-term transition pathways (e.g. 2020–2050)

INTEROPERABILITY

The ability of different systems and datasets to work together, ensured through:

- ✓ standardized identifiers (e.g. Building_ID, Block_ID)
- ✓ consistent data formats
- ✓ unified units and KPIs

1.5. Transnational Dimension

The transnational nature of this protocol is reflected in:

- ✓ the harmonization of methodologies across different countries and data contexts
- ✓ the definition of a minimum common dataset applicable to all pilots
- ✓ the inclusion of flexibility mechanisms for adapting to local data availability

This ensures:

- ✓ comparability of results between pilot areas
- ✓ transferability of the methodology
- ✓ long-term usability beyond the project

B. METHODOLOGICAL FRAMEWORK

2.1 General Approach

The development of neighbourhood digital twins within the ZEB4ZEN project follows a structured, multi-step methodological framework that integrates data collection, spatial modelling, energy analysis, and decision-support functionalities.

The approach is based on:

- ➢ a bottom-up modelling principle, starting from individual buildings
- ➢ spatial aggregation to block and neighbourhood level
- ➢ integration of energy, environmental, and socio-economic data

- alignment with digital tools for visualisation and scenario evaluation

This framework ensures consistency across pilot cities while allowing sufficient flexibility to account for differences in local data availability, urban morphology, and heritage constraints.

The methodology combines the GIS-based digitalization workflow and the data structure required for digital twin platforms, resulting in a harmonised protocol for transnational application.

2.2 Key Analytical Steps

The development of a neighbourhood digital twin is organized into five main phases, each consisting of clearly defined steps.

PHASE 1: DATA COLLECTION AND STRUCTURING

This phase establishes the data foundation of the digital twin.

Key activities include:

- collection of building-level data, including:
- administrative data (ID, address, location)
- technical characteristics (area, number of storeys)
- heritage attributes
- energy baseline data
- compilation of data in structured tabular formats (e.g., Excel)
- standardization of data fields and formats

The structured dataset follows a“one row – one building” approach, enabling compatibility with GIS and analytical tools.

PHASE 2: SPATIAL INTEGRATION AND GIS MODELLING

In this phase, tabular data is linked to spatial geometries.

Key steps include:

- preparation of spatial layers (building polygons, block boundaries)
- linking tabular data to spatial data using unique identifiers (e.g., cadastral parcel number, Building_ID)
- validation of spatial accuracy and completeness
- integration of additional layers (orthophotos, infrastructure, public lighting)

This step ensures the creation of a georeferenced digital model of the neighbourhood, forming the basis for further analysis and visualisation.

PHASE 3: AGGREGATION AND KPI LAYER DEVELOPMENT

Building-level data is aggregated to support planning and analysis at higher spatial scales.

Key activities:

- grouping buildings into blocks (spatial planning units)

- aggregation of key indicators per block:
- energy consumption
- CO_2 emissions
- installed capacity
- energy intensity (per m^2)
- generation of a KPI layer within the GIS environment

This aggregation facilitates:

- comparison between different zones
- identification of priority areas for intervention
- support for scenario modelling

PHASE 4: SCENARIO MODELLING AND ANALYSIS

This phase introduces future-oriented modelling within the digital twin.

Key elements include:

Definition of EE/RES measures, such as:

- thermal insulation
- heating system upgrades with renewable energy integration (PV, heat pumps, district heating)

Simulation of different scenarios:

- baseline scenario
- alternative intervention scenarios
- calculation of key performance indicators:
- energy savings (MWh)
- CO_2 reduction (tCO_2)
- investment costs (€)

Scenarios are modelled both at:

- building level
- block level
- neighbourhood level
- and can include long-term trajectories (e.g., 2020–2050)

PHASE 5: INTEGRATION WITH DIGITAL TWIN PLATFORM

The final phase integrates the developed datasets into a digital twin environment (e.g., VR platform).

Key requirements include:

Structured datasets aligned with:

- metadata layers

- scenario layers
- multicriteria analysis inputs
- compatibility with spatial formats (GIS, BIM, 3D models)

Preparation of data for:

- interactive visualisation
- scenario comparison
- stakeholder engagement

The digital twin enables:

- real-time exploration of scenarios
- visual representation of energy and spatial impacts
- structured decision-making processes

2.3 Transnational Harmonisation Principles

To ensure consistency across all pilot cities, the following principles apply:

- Standardization of data structures
- Use of common identifiers (Building_ID, Block_ID)
- Consistency of units and KPIs (MWh, tCO_2, €)
- Alignment of scenario definitions
- Compatibility with common digital tools

At the same time, the protocol allows:

- flexibility in data sources
- adaptation to national datasets
- gradual improvement of model detail

C. DATA REQUIREMENTS AND STANDARDIZATION

3.1 General Data Framework

The development of neighbourhood digital twins requires a structured and harmonized data framework that ensures:

- consistency across pilot cities
- interoperability between tools (GIS, Excel, VR platforms)
- comparability of results at transnational level

The data framework is based on the integration of:

- spatial data (GIS, 3D models, point clouds)
- semantic data (building attributes, energy parameters)
- scenario data (EE/RES measures and projections)

All datasets must follow a standardized structure, enabling seamless linkage between:

- tabular data
- spatial layers
- digital twin platforms

3.2 Data Categories

The protocol defines four main categories of data required for digital twin development.

3.2.1 Building Metadata

Building metadata provides the core descriptive layer of the digital twin and includes:



Administrative Data

Building ID, address, cadastral parcel number, and coordinates. Technical data includes useful area, number of storeys, and building typology.

Cultural Heritage Data

Heritage protection level, construction period, and renovation constraints.

Energy Baseline Data

Heating system type, energy consumption in MWh/year, and CO_2 emissions in t/year.

Socio-Economic Data

Ownership, physical condition, and energy poverty indicators.

These data are structured in tabular format using a one-record-per-building approach, enabling linkage with GIS systems and analytical models.

3.2.2 EE/RES Measures Dataset

This dataset defines the interventions applied in scenario modelling.

Each record must include:



Identification Fields
Building_ID/Block_ID, measure type (e.g., insulation, PV, heat pump)

Technical Indicators
Energy savings (MWh), renenewable energy generation

Environmental Indicators
CO_2 emissions and reductions

Economic Indicators
CAPEX (€), OPEX (€), energy cost savings

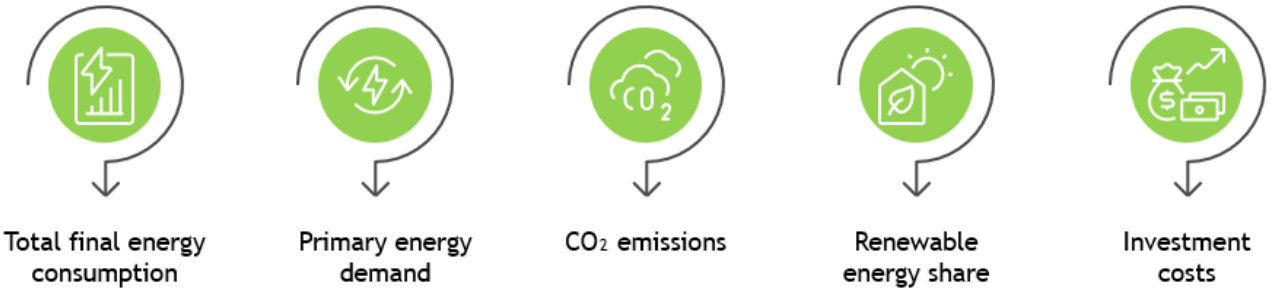
Performance Indicators
Payback period, energy intensity improvements

The dataset must allow comparison between baseline and improved scenarios and support recalculation under different assumptions.

3.2.3 KPI and Aggregated Data Layer

Aggregated datasets are developed at block and neighbourhood levels.

Key indicators include:



Aggregation is performed using block identifiers and spatial grouping of buildings. This enables the creation of a KPI layer for spatial analysis and planning, supporting prioritization and decision-making.

3.2.4 Scenario and Time-Series Data

This dataset represents the evolution of the neighbourhood over time.

Required elements include:

- timeline (e.g. 2020-2050
- implementation year of each measure

Yearly updates of:

- energy consumption
- CO_2 emissions
- investments

This allows the digital twin to simulate:

- phased implementation strategies
- long-term decarbonization pathways
- cumulative impacts of interventions

3.3 Data Structuring and Formats

To ensure compatibility, all datasets must follow standardized formats:

3.3.1 Tabular Data

format: .XLSX or .CSV

structure:

- one row per entity (building, block, measure)
- consistent column naming conventions
- encoding: UTF-8 (recommended for international compatibility)

3.3.2 Spatial Data

- building and block geometries stored as:
  - polygon shapefiles or geodatabases
- coordinate reference system:
  - national CRS or standardized European CRS (recommended)

3.3.3 3D and Visualization Data

Supported formats include:

- point clouds: .LAS, .E57
- 3D models: .FBX, .GLB
- orthophotos: .TIFF
- CAD drawings: .DWG

These formats enable integration with digital twin visualization platforms.

3.4 Data Interoperability Requirements

To ensure integration across tools and datasets, the following requirements apply:

3.4.1 Unique Identifiers

All datasets must use consistent identifiers:

- Building_ID
- Block_ID
- Pilot_City

These identifiers ensure:

- linkage between spatial and tabular data
- traceability across datasets
- compatibility with digital twin environments

3.4.2 Consistent Units and Metrics

All partners must use standardized units:

- ParameterUnitEnergyMWh/yearCO_2 emissionstCO_2/yearInvestment cost€/m^2
- This ensures comparability of results across pilot cities.

Scenario Comparability

All scenarios must include:



Each measure must provide:



This enables cross-country comparison and benchmarking.

3.5 Minimum Data Requirements (Transnational Baseline)

To ensure applicability across all pilot cities, a minimum dataset is defined.

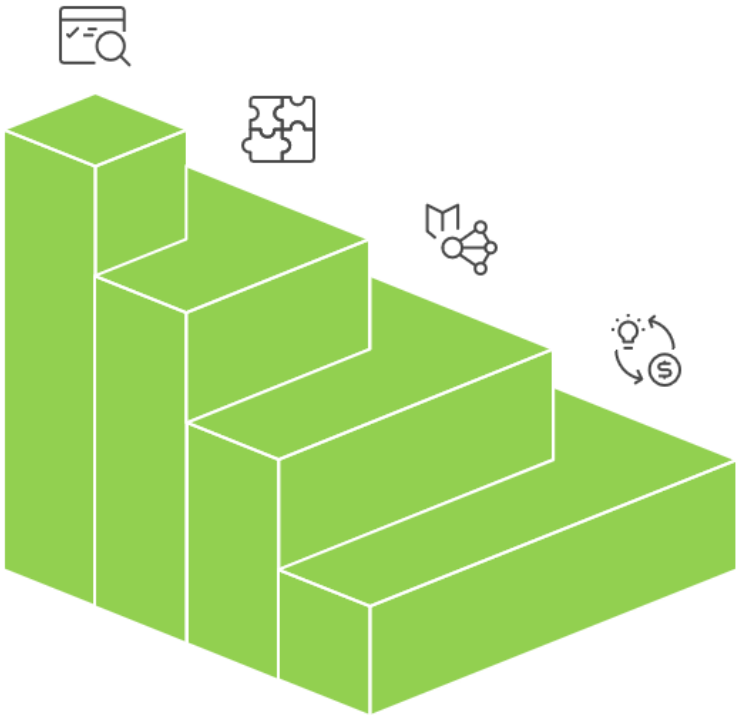
Each partner must provide at least:

- building geometry
- Building_ID
- building use type
- floor area
- baseline energy consumption
- heating system type
- block identifier
- CO_2 emissions
- cost data
- socio-economic indicators

This approach ensures participation even in cases of limited data availability, while enabling gradual model enhancement.

3.6 Data Quality and Validation

To ensure reliability of the digital twin, the following validation steps are required:



Where data gaps exist:

- default values or assumptions may be applied
- assumptions must be documented

3.7 Flexibility and Adaptation

While standardization is essential, the protocol allows:

- use of national datasets and classification systems
- adaptation to local data availability
- progressive refinement of datasets over time

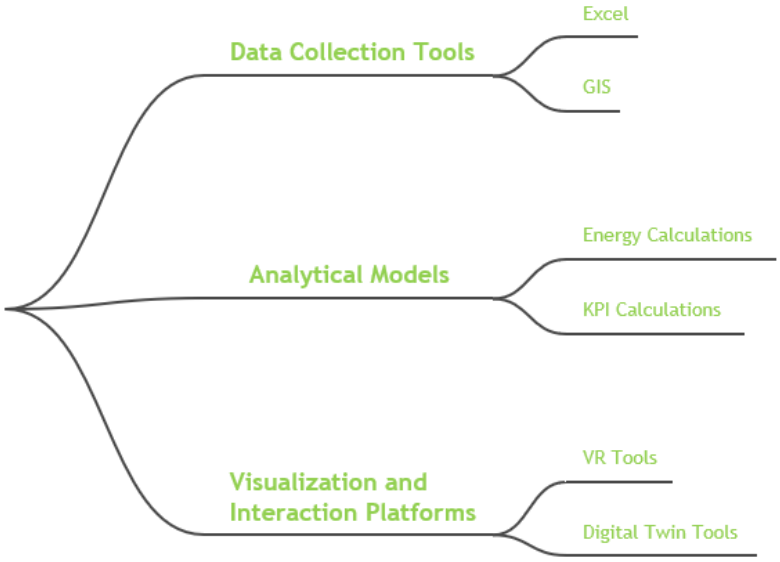
This ensures:

- practical usability across different countries
- scalability to future applications
- alignment with transnational cooperation principles

D. INTEROPERABILITY AND SYSTEM INTEGRATION

4.1 General Integration Concept

The neighbourhood digital twin is conceived as an integrated system of interoperable components, combining:



The system architecture ensures that:

- data flows seamlessly between components
- updates can be propagated across the system
- results are visualized and used for decision-making

The integration is based on a layered approach, where each component performs a specific function within the overall workflow.

4.2 System Architecture Overview

The digital twin system is composed of the following key layers:

1. DATA LAYER

This layer includes all structured datasets:

Building metadata:

- EE/RES measures datasets
- scenario and KPI data

Data are stored in tabular formats (Excel/CSV) and represent the core information source for the digital twin.

2. SPATIAL LAYER (GIS INTEGRATION)

The spatial layer links data to geographical context through GIS.

Main components:

- building polygons
- block geometries
- infrastructure layers

This layer enables:

- spatial analysis
- visualization of energy indicators
- mapping of intervention priorities

3. ANALYTICAL LAYER

The analytical layer contains:

- energy modelling tools
- KPI calculation frameworks
- scenario simulation models

It processes raw data into:

- energy demand profiles
- CO_2 emissions
- cost indicators

This layer provides the quantitative backbone of the digital twin.

4. VISUALIZATION AND INTERACTION LAYER

This layer is represented by the digital twin platform (e.g., VR tool), enabling:

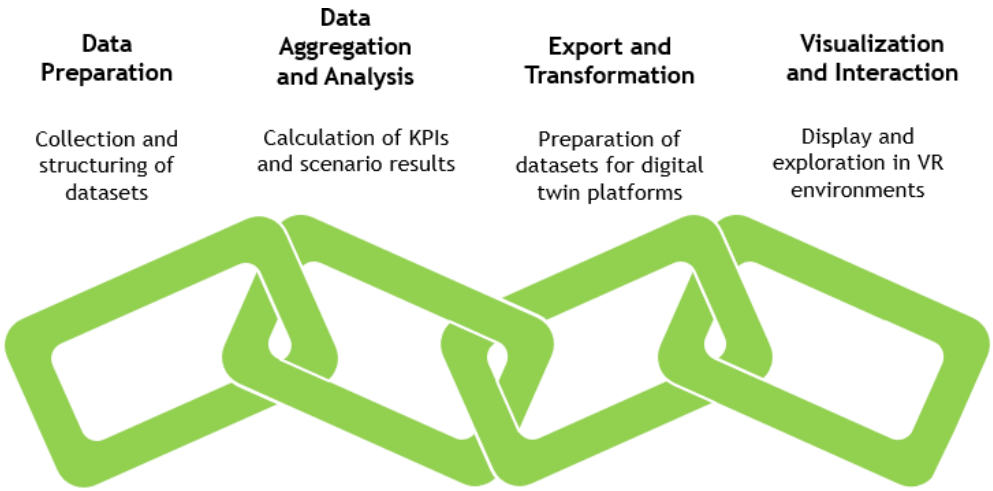
- interactive exploration of the neighbourhood
- visualization of baseline and scenario data
- comparison of alternative interventions

It supports:

- stakeholder engagement
- collaborative planning
- decision-making processes

Data Flow and Integration Process

The integration of the digital twin is based on a sequential data flow:



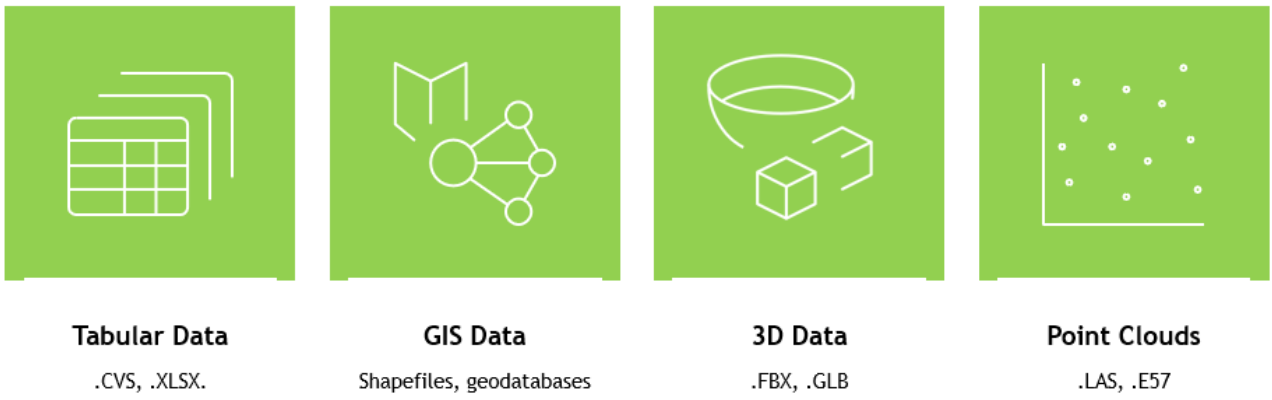
This structured process ensures that all components operate within a consistent and traceable workflow.

4.3 Interoperability Mechanisms

To guarantee interoperability across different tools and platforms, the following mechanisms are applied:

STANDARDIZED DATA FORMATS

Interoperability is ensured through the use of widely accepted formats:



This enables integration with both:

- GIS environments
- VR-based digital twin tools

CONSISTENT DATA MODELS

All datasets follow consistent data models, including:



Identical Variable Naming



Unified Data Structures



Standard Units and KPIs

This ensures that:

- datasets can be reused across pilots
- results are comparable
- tools can process data without additional transformation

4.4 Integration with Decision-Support Tools

A key feature of the digital twin is its integration with decision-support mechanisms, particularly:

- multicriteria analysis (MCA)
- scenario ranking tools

The integration allows evaluation of measures based on:

- technical performance
- economic feasibility
- environmental impact
- dynamic adjustment of priorities by users

This functionality enables a shift from static data analysis to interactive planning and decision-making.

4.5 Scalability and Replicability

The system architecture is designed to support:

Scalability

- extension to larger urban areas,
- inclusion of additional datasets,(e.g., mobility, infrastructure)
- integration of new analytical tools.

Replicability

- application in other cities,
- adaptation to different regulatory and data contexts,
- reuse of the same methodological framework.

This ensures that the digital twin approach can be transferred beyond pilot areas and used in future projects.

4.6 Data Management and Maintenance

For long-term usability, the system must support:

- regular data updates
- version control of datasets
- secure storage and access management

Responsibilities include:

- data validation before updates
- maintenance of data structure consistency
- documentation of changes

This ensures the digital twin remains accurate, reliable and relevant over time.

E. CONCLUSION

The Transnational Protocol for Neighbourhood Digital Twin Development provides a structured and harmonized approach to the creation and use of digital twins in the context of energy planning for historical urban areas. By integrating methodologies for data collection, spatial modelling, energy analysis, and digital visualization, the protocol ensures that digital twin development is technically robust, methodologically consistent, and applicable across different national contexts.

A key contribution of the protocol lies in its transnational dimension, enabling alignment of approaches across pilot cities, comparability of results and indicators, and transfer of knowledge and solutions between countries.

The protocol successfully combines GIS-based analytical workflows, structured data models, and interactive digital twin platforms into a unified system that supports both detailed technical analysis, and participatory and transparent decision-making.

The definition of standardized datasets, interoperability requirements, and minimum data conditions ensures that the approach is adaptable to varying data availability, scalable to larger urban systems, and replicable in other cities and regions.

Furthermore, the integration of scenario modelling and multicriteria analysis enables stakeholders to assess alternative energy strategies, evaluate impacts across technical, economic, and environmental dimensions support evidence-based planning for Zero-Emission Neighbourhoods

In conclusion, the protocol establishes a solid foundation for the systematic development of neighbourhood digital twins, contributing to:

- ✓ more efficient and coordinated urban energy planning
- ✓ improved stakeholder engagement and communication
- ✓ acceleration of the transition towards climate-neutral urban environments

Its application within the ZEB4ZEN project demonstrates the potential of digital twin technologies to bridge the gap between technical analysis and practical implementation, particularly in complex, heritage-sensitive urban contexts.