en couverture
Exercice de représentation BAC2 LOCI Tournai
Musée L, Louvain-la-Neuve, Belgique
Photo Corentin Haubruge (septembre 2025).

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Louvain research institute for Landscape, Architecture, Built environment

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Spatial data and methods for urban planning and architecture

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Abstract. *Spatial data plays a foundational role in urban design and architecture by capturing the physical, social, and environmental dimensions of urban contexts. The proliferation of spatial data has introduced challenges in data quality, granularity, and interoperability: a profound methodological turn especially for disciplines ordinarily confronted to spatial "challenges" such as architecture, urbanism and engineering. We can surely state that within these disciplines the increased employment of GIS platforms and spatial programming frameworks is enabling a revolution of the means of spatial representation, yet the mathematical disciplines informing spatial data analysis remain obscure for many users. The article aims to unveil the complex analytical operations underpinning spatial analysis tools to reveal how spatial analysis is informing decision-making across urban planning and infrastructure management in increasingly complex urban environments.*

Keywords. *spatial data · spatial analysis · GIS · mapping · cartography*

Résumé. *Les données spatiales jouent un rôle fondamental dans l'urbanisme et l'architecture en capturant les dimensions physiques, sociales et environnementales des contextes urbains. La prolifération des données spatiales a introduit des défis en matière de qualité, de granularité et d'interopérabilité des données : un profond changement méthodologique, en particulier pour les disciplines habituellement confrontées à des "défis" spatiaux telles que l'architecture, l'urbanisme et l'ingénierie. Nous pouvons affirmer sans hésitation que, dans ces disciplines, l'utilisation croissante des plateformes SIG et des cadres de programmation spatiale est en train de révolutionner les moyens de représentation spatiale, mais les disciplines mathématiques qui sous-tendent l'analyse des données spatiales restent obscures pour de nombreux utilisateurs. Cet article vise à dévoiler les opérations analytiques complexes qui sous-tendent les outils d'analyse spatiale afin de révéler comment l'analyse spatiale influence la prise de décision en matière d'urbanisme et de gestion des infrastructures dans des environnements urbains de plus en plus complexes.*

Mots-clés. *données spatiales · analyse spatiale · SIG · mapping · cartographie*

Spatial Data Requirements

Urban design and architecture rely on spatial data to capture the broader context and nuanced details on the physical, social, and environmental context of a site or urban area. Spatial data needs to efficiently satisfy key *requirements* such as site suitability, infrastructures, demographics, socio-economic and/or cultural composition, environmental condition and challenges and so on. Historically these needs have been addressed by paper maps at suitable scales with *topographic and thematic cartography*. Today, the proliferation of digital spatial data and digital processing capabilities has not only revolutionized the way we manage data, but also knowledge discovery.

Spatial data sources and data preparation

Recently, digital data sources have exploded both in volume and diversity, particularly within the context of urban environments. A wide array of stakeholders that include local and regional governments, national and international agencies, volunteer communities, and private enterprises, now contribute to the availability of spatial data. Data can be located as well-structured data stored in *data warehouses* typically curated by public authorities or large private companies, and to the more loosely organized, semi-structured or unstructured data aggregated from heterogeneous sources in *data lakes*. An example of the first storage method is Cadastral data, which are characterized by extremely high data quality requirements and must produce accurate results for strict search queries and support transactions. A data lake may contain a variety of data such as social data from disparate sources such as crowdsourcing, real-time sensor feeds, or social media. Unlike data warehouses, data lakes generally lack strict organizational schemas or validation protocols, which means they may store incomplete, inconsistent, or outdated data of varying quality. However, their advantages include speed, flexibility, low cost, broad subject coverage, and access to data that might otherwise be unavailable through traditional systems. Thus, the accuracy, reliability, timeliness, spatial granularity and overall quality vary among these sources and affect the suitability for usage for each requirement. Most of this data will require preprocessing such as data cleansing, data transformation, normalization, georeferencing or reprojection etc.

Spatial methods and their foundations

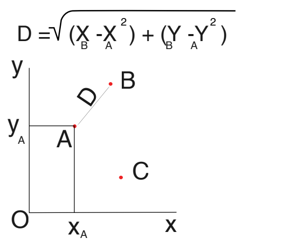
When spatial datasets are well-structured, they can be seamlessly managed through CAD software. CAD environments facilitate the visualization and manipulation of spatial features, thereby supporting design-centric workflows with minimal preprocessing. However, when extensive preprocessing, integration, or analytical interpretation is necessitated, the application of advanced spatial analysis tools is essential. These tools include Geographic Information System (*GIS*) platforms, as well as *spatially enabled programming frameworks*, such as SQL with spatial extensions, or high-level languages like Python utilizing spatially oriented libraries. These environments offer robust capabilities for combining geometric data with descriptive attributes.
Underlying the functionality of spatial analysis tools is a suite of mathematical disciplines that inform both algorithmic design and analytical procedures. Key domains include:

Analytical geometry provides the mathematical foundation for coordinate representation, geometric modeling, and spatial transformations (Fig. 1.1). It enables the quantification of spatial properties such as distance, area, volume, azimuth, and vertical angles (Fig. 2.1). Spatial entities in the real world can be abstracted as geometric objects across dimensions: points i.e. for locations (0D), lines for roads (1D), polygons for zones (2D), and polyhedra for buildings (3D). This framework supports essential transformation operations including editing, scaling, translation, rotation, and buffering. As a core component of digital spatial data representation, analytical geometry plays a role analogous to that of CAD systems in engineering and design.

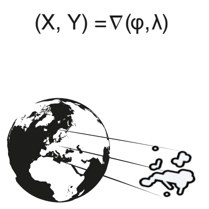
Projective geometry underpins the transformation of the Earth's three-dimensional surface into two-dimensional map representations (Fig. 1.2). It forms the theoretical foundation of cartography and maintains a close association with geodesy. Given the inherent limitations of map projections, it is impossible to simultaneously preserve shape, area, and directional accuracy. Consequently, the selection of a projection method is guided by the intended application of the map. For example, the widely recognized Mercator projection has historically been favored for navigation due to its preservation of directional fidelity, although it introduces significant distortions in shape and scale, particularly near the polar regions (Fig. 2.2).

Topology examines the spatial relationships between geometric entities, focusing on properties such as adjacency, connectivity, containment, intersection, and proximity (Fig. 1.3). These relationships enable the abstraction and analysis of real-world spatial interactions beyond mere geometric form. Topological representations emphasize relational structure rather than precise spatial positioning. For instance, topological maps illustrate how features are connected or ordered, without necessarily reflecting their geographic coordinates. A common example is a public transportation map, which conveys the sequence and connectivity of stops while omitting accurate spatial distances or orientations (Fig. 2.3).

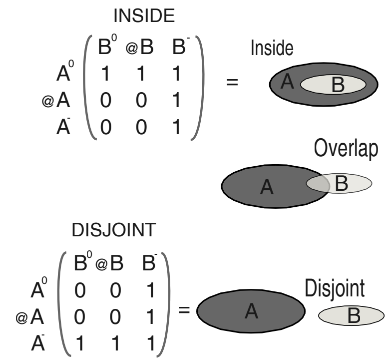
Set theory provides a conceptual basis for representing polygonal spatial objects as sets, whose elements correspond to the locations enclosed within the polygonal boundary (Fig. 1.4). Through set-theoretic operations—such as union, intersection, clipping, and symmetrical difference—GIS enables spatial analyses that integrate geometric configurations with attribute data. These operations support selection and overlay techniques that yield both spatial and descriptive outcomes. For instance, an Area of Interest (AOI) can be used to



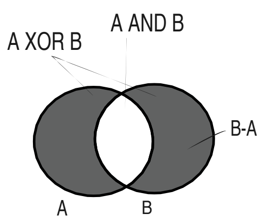
1. Analytical geometry



2. Projective geometry



3. Topology

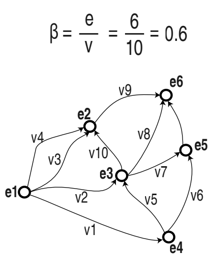


4. Set Theory

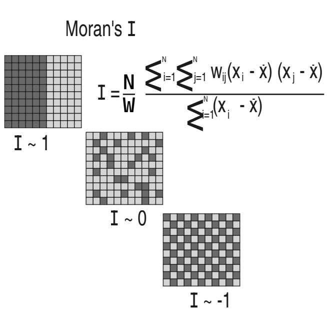
$\boxed{1 + 1 = 1}$

SELECT polys
WHERE condition_A equals TRUE AND
condition_B equals TRUE

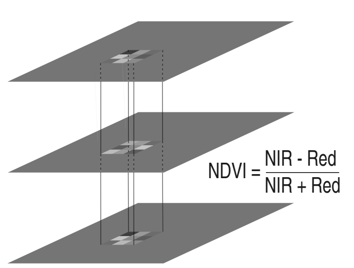
5. Boolean Logic



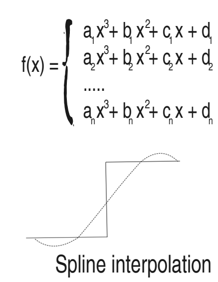
6. Graph theory



7. Geostatistics

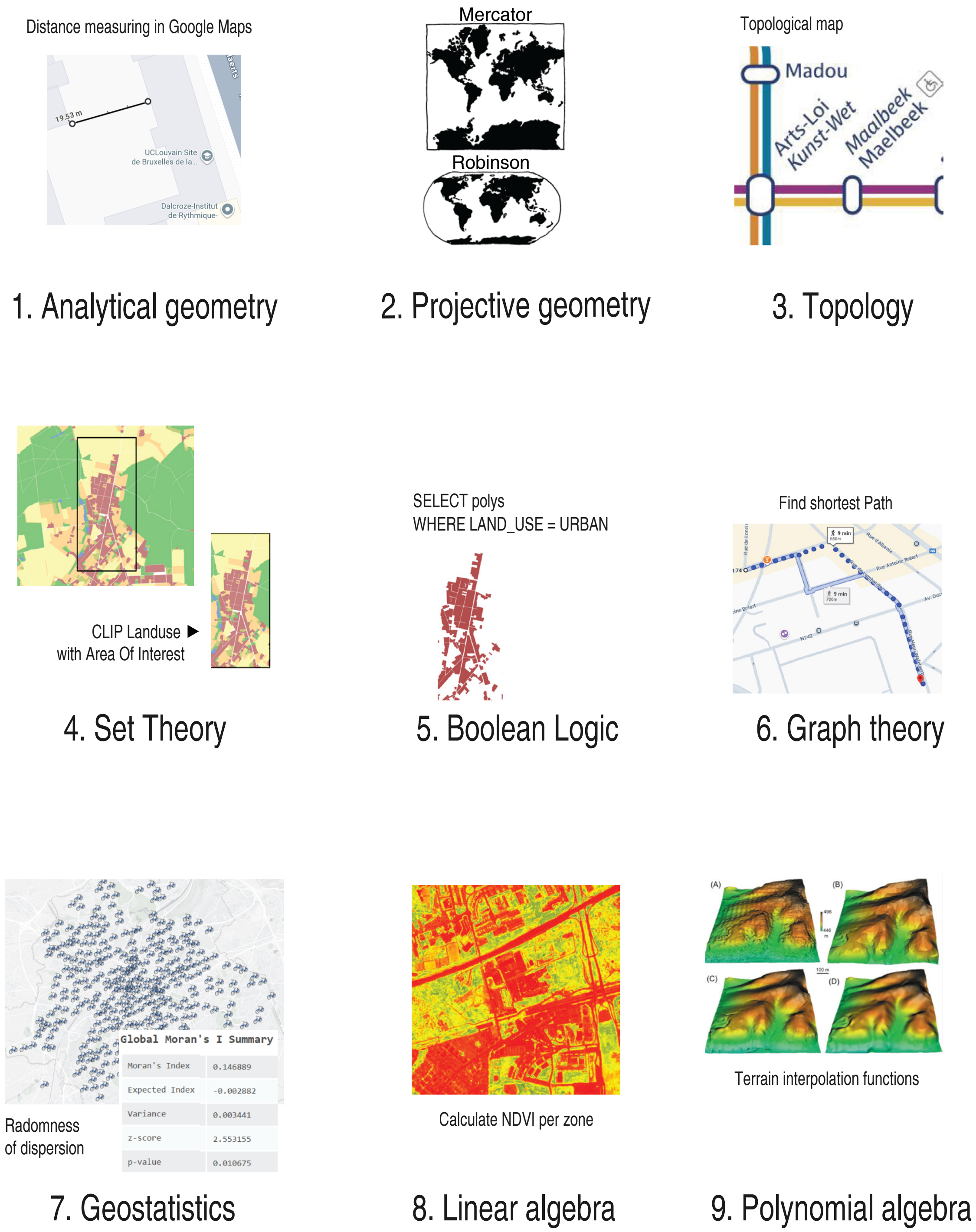


8. Linear algebra



9. Polynomial algebra

1. Mathematical Foundations
1.1 Analytical Geometry
1.2 Projective Geometry
1.3 Topology
1.4 Set Theory
1.5 Boolean Algabra
1.6 Graph Theory
1.7 Geostatistics
1.8 Linear Algebra
1.9 Polynomial Algebra
1.1-1.9 Elaboration by author



(1) Examples of applications of the mathematical foundations in spatial data processing and analysis
2.1 Distance measurement on Google Maps by author
2.2 World Map Representation (iNatForum)
2.3 Extract from Brussels Metro Map (STIB)
2.4 Clip example by author
2.5 SQL select example by author
2.6 Navigation (shortest path) in Google Maps by author
2.7 Moran's I calculation by author
2.8 NDVI index in Sentinel hub image
2.9 Interpolation surfaces (University of Alberta)

exclude all features from multiple layers that lie outside its boundary by applying the clipping overlay function (Fig. 2.4).
Boolean logic operates on binary values—TRUE (1) and FALSE (0)—and is formalized through Boolean algebra (Fig. 1.5). In this framework, operations such as 1+1=1 signify that the logical conjunction of two TRUE conditions yields a TRUE outcome. Within GIS, Boolean logic is implemented through structured query languages (SQL), including spatial SQL, to perform attribute-based and spatial selections. For example, a query selecting all polygons classified with the land use attribute "Urban" demonstrates the application of Boolean conditions in spatial data filtering (Fig. 2.5).

Graph theory provides a mathematical framework for representing networks through nodes (vertices) and their interconnections via edges (Fig. 1.6). This structure enables the modeling and analysis of various real-world systems, including transportation, water distribution, and communication networks, along with their operational characteristics and dynamic behaviors. One of the most prominent applications of graph theory in GIS is the shortest path algorithm, which underlies navigation systems by identifying the most efficient route between two locations (Fig. 2.6) optimized according to various criteria such as travel distance, travel time, transportation cost or the most scenic route.

Geostatistics is a specialized branch of statistics adapted to account for the spatial dimension of data (Fig. 1.7). It enables the examination of spatial correlations, distributional patterns, and hypothesis testing within geographically referenced datasets. For instance, the spatial arrangement of Villo bike-sharing stations in Brussels can be analyzed using Moran's I to assess the degree of spatial autocorrelation. A computed Moran's I value of 0.147 suggests a statistically significant deviation from randomness, indicating that the distribution of stations exhibits spatial clustering (Fig. 2.7).

Linear algebra provides the mathematical foundation for matrix-based computations and linear transformations within GIS (Fig. 1.8). Raster datasets, typically structured as M×N matrices of cell values (often mentioned as pixels), can be analyzed through cell-by-cell overlays across multiple layers or by applying roving window operations to compute localized statistics. These techniques enable advanced spatial analysis, particularly in remote sensing applications. A notable example is the Normalized Difference Vegetation Index (NDVI), which quantifies vegetation density by processing reflectance values from the red and near-infrared spectral bands captured by satellite imagery (Fig. 2.8).

Polynomial algebra is primarily applied in GIS for interpolation techniques that generate terrain and trend surfaces (Fig. 1.9). These methods fit polynomial functions to spatial data points to estimate values across unsampled areas. The final shape of a terrain surface depends not only on the input data but also on the chosen interpolation method, which influences the smoothness and accuracy of the result (Fig. 2.9). Beyond interpolation, polynomial expressions are also used in modeling and transforming raster data, supporting analytical tasks such as surface fitting and environmental prediction.

These mathematical methodologies are integral to multiple stages of the GIS analytical workflow, particularly during the data preparation and data analysis phases. In the preparation phase, they support tasks such as spatial data transformation, interpolation, and geometric structuring. During analysis, they enable operations like pattern detection, spatial querying, statistical modeling, and network optimization, thereby enhancing both the precision and interpretability of spatial insights.

Presenting and exploiting spatial data

Spatial data and spatial analysis results are most effectively communicated with maps supplemented by graphs or tables. Conventionally, static maps rendered in print or digital formats offer a static view. The choice of symbols, color schemes, text formatting and accompanying map elements, such as the legend, are governed by the principles of cartography and establish the readability and the value of the map for the indented use. However, today *dynamic maps* have become increasingly prevalent. Typically web-based, they enable real-time data exploration, multiple scales mapping and updates such as *topomap viewer* or MobiGIS. By granting access to the underlying thematic information in descriptive form, by facilitating the generation of customized maps and by performing on-demand online spatial analysis, they have gradually evolved to fully developed *web services*.
In contemporary urban systems, the integration of spatial data and GIS functionalities has become increasingly central to the development of Smart Cities and City Digital Twins. While these

frameworks share objectives—such as enhancing urban efficiency, sustainability, and responsiveness—they differ in scope, technological implementation, and operational focus. Smart Cities emphasize real-time data-driven governance and service optimization, whereas City Digital Twins offer dynamic, virtual replicas of urban environments for simulation, planning, and predictive analysis. Together, they are reshaping the paradigm of spatial data utilization across sectors such as urban planning, infrastructure management, and architectural design, fostering more informed decision-making and adaptive urban strategies.

According to the United Nations Economic Commission for Europe, a *smart city* is *an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects*. It is based on data collection encompassing all the domains of a city, regardless of the temporal variability.

A *digital twin* refers to a virtual replica of a physical system of interest—such as a city—that facilitates the assessment and management of past, present, and prospective scenarios, whether anticipated, planned, or arising from emergency conditions. A principal advantage of the digital twin paradigm lies in its capacity to analyze multiple interrelated domains concurrently, rather than in isolation. This is achieved by integrating geospatial data derived from GIS and smart city infrastructures, and even *BIM data* and importing them to dynamic models which simulate the operation of the city. The operation of the city is the combined results of the simulation of divergent constituent subsystems that may belong to separate domains such as land use change, demographics, commercial and financial activities, traffic flows, environmental performance or hydrological networks, to name just a few. The models collectively inform decision-making processes and operational responses across both routine and crisis situations, thereby enhancing urban resilience and governance.

Spatial data and analytical methodologies have long been integral to the disciplines of architecture and urban planning.

Spatial data contemporary trends, however, contribute increasingly to a comprehensive and systemic understanding and communication of the urban fabric and its functional dynamics. ■

AI has been used for rephrasing parts of the document.

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