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URBANSENSE: INTEGRATING HUMAN PERCEPTION INTO URBAN DIGITAL TWIN - A CAMPUS-SCALE CASE STUDY OF PERCEIVED CONVIVIALITY AND URBAN POLLUTION

URBANSENSE : INTÉGRATION DE LA PERCEPTION HUMAINE DANS LE JUMEAU NUMÉRIQUE URBAIN - ÉTUDE DE CAS DE LA CONVIVIALITÉ ET DE LA POLLUTION URBAINE PERÇUES À L'ÉCHELLE DU CAMPUS

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Abstract
Given the rapid urbanization currently underway worldwide, Urban Digital Twins (UDTs) have emerged as powerful tools for simulating, monitoring, and planning cities. However, most UDTs remain primarily technical, focusing on physical infrastructures, sensors, and environmental data, while overlooking citizens' subjective perceptions. This article introduces a human-centric framework integrating perception data into standardized 3D city models. The methodology was tested on Sart-Tilman Campus, University of Liège (Belgium), where pedestrian routes were segmented and assessed through a field survey based on ten perceptual factors. Results were normalized, aggregated into perception scores, and processed through a dedicated pipeline before being visualized in a custom web platform, UrbanSense (CesiumJS). Findings demonstrate that subjective data can be systematically integrated into UDTs, supporting participatory planning and more inclusive urban analysis, and highlighting the feasibility of standardized, human-centric UDTs bridging technical modeling and citizens' lived experiences.

Keywords
human-centric urban digital twin, perception data, cesium, conviviality, pollution; urbansense, participative urban planning

Résumé
Dans un contexte d'urbanisation croissante, les jumeaux numériques urbains (Urban Digital Twins - UDTs) ont émergé comme des outils puissants pour simuler, surveiller et planifier les villes. Toutefois, la plupart des UDTs demeurent principalement techniques, centrés sur les infrastructures physiques, les capteurs et les données environnementales, au détriment des perceptions subjectives des citoyens. Cet article propose un cadre conceptuel centré sur l'humain, intégrant des données de perception dans des modèles urbains 3D standardisés. La méthodologie a été testée sur le campus de l'Université de Liège (Belgique), où les itinéraires piétons ont été segmentés et évalués via une enquête de terrain basée sur dix facteurs perceptifs. Les résultats ont été normalisés et agrégés en scores de perception, puis traités dans une chaîne dédiée et visualisés sur une plateforme web personnalisée, UrbanSense (CesiumJS). Les résultats montrent que les données subjectives peuvent être systématiquement intégrées dans les UDTs, ouvrant des perspectives pour la planification participative et une analyse urbaine plus inclusive. Le cadre met en évidence la faisabilité de UDTs standardisés, évolutifs et centrés sur l'humain, reliant modélisation technique et expérience vécue des citoyens.

Mots-clés
jumeaux numériques urbains centrés sur l'humain, données perceptuelles, cesium, convivialité, pollution, urbansense, planification urbaine participative

INTRODUCTION

In response to contemporary urban challenges such as pollution, liveability, and the quality of urban experience, Urban Digital Twins (UDTs) have emerged as promising tools for managing this complexity (Luo *et al*., 2025; Qanazi *et al*., 2025; Q.-C. Wang *et al*., 2025). By combining real-time data streams, advanced 3D modeling, and simulation techniques, UDTs provide valuable support for decision-making spanning multiple domains such as mobility, energy, environmental management, and urban planning (Pourroostaei *et al*. 2024; Lehtola *et al*. 2022).

Despite the recognized advances in UDTs, current implementations are particularly effective in representing what may be termed the objective layers of the city (Luo *et al*., 2025; Qanazi *et al*., 2025), to name a few: the physical layer

(buildings, roads, vegetation), the technical layer (networks of sensors and monitoring systems), and the infrastructure layer (energy grids, transportation systems, and other utilities). Yet, a critical dimension for urban analysis and decision-making remains largely overlooked in existing UDT frameworks: the human perception layer (Lei *et al*. 2024; Lei *et al*. 2024; Qanazi *et al*. 2025). This layer reflects how individuals experience and interpret their environment (Luo *et al*., 2025; Qanazi *et al*., 2025), for example: their sense of comfort, safety, sociability, or exposure to pollution. Current Urban Digital Twins (UDTs) remain predominantly centred on the physical and measurable dimensions of urban environments, thereby modelling the city primarily as a space rather than as a place. Such an orientation tends to overlook the subjective and experiential dimensions through which urban environments are perceived, inhabited, and socially constructed. Yet, these dimensions are fundamental to understanding urban liveability and quality of life. As a result, many existing UDTs remain techno-centric and insufficiently responsive to the social realities and human experiences that shape the meaning of urban environments (Azadi *et al*., 2025; Lei, Liang, *et al*., 2024).

This concept has been increasingly adopted in urban studies to explore the complex interactions between individuals and the urban systems, as well as the potential of integrating the human layer in UDTs to better understand the urban environment (Luo *et al*. 2025; Lei *et al*. 2024; Lei *et al*. 2024; Liu *et al*. 2023). Therefore, human perception emerges not only as a data source but as a critical lens for understanding urban quality, highlighting the importance of human-centric approaches in planning more inclusive cities.

The challenge lies not only in identifying effective ways to integrate human perception into UDT components, but also in determining how it can be meaningfully modelled. Unlike physical and technical attributes, subjective dimensions of the urban environment, such as emotions, lived experiences, and aesthetic perceptions, are inherently difficult to assess and quantify. The central task, therefore, is to translate these subjective dimensions into structured, interpretable, and actionable forms of data that can support urban analysis and inform decision-making (Jayathissa *et al*., 2020; Lei, Liang, *et al*., 2024; Qanazi *et al*., 2025).

In this context, few studies have addressed this challenge and investigated the integration of human data within technical frameworks. Existing work has made important contributions in data collection methodologies and on human interaction with urban digital twins during later stages of implementation. As a result, existing UDTs remain constrained in their capacity to support inclusive urban planning, foster meaningful citizen engagement, and inform decision-making processes that are socially responsive and equitable.

To address these concerns, there is a need for a methodological framework capable of systematically collecting, processing, and connecting human perception data with the objective spatial layers of the city, while ensuring scalability to cover wider scales of the urban environment. Therefore, our study is guided by a central research question: *How can human perception data be systematically integrated into Urban Digital Twins to support more human-centric representations of urban environments?*

In response, we propose and test a Human-Centric UDT framework through a real-world case study conducted on Sart-Tilman campus of the University of Liège (Belgium). The study:

- Developed and implemented a field survey to capture citizen perceptions of conviviality and pollution along pedestrian routes;
- Designed a data processing pipeline to normalize, weight, and aggregate responses into segment-level perception scores;
- Built a web-based platform, *UrbanSense*, for interactive three-dimensional visualization of results using CesiumJS.

I. STATE OF THE ART

Human-Centric Urban Digital Twin are designed with citizens as core contributors through all stages, recognizing that, as frequent users of urban landscapes, they are well positioned to identify relevant issues and contribute significantly to maintaining and improving city ecosystems (Qanazi *et al*., 2025). In a human-centric digital

twin, the human is the pivotal element in the DT ecosystem and the center of its structure by which the built environment is learned, described, observed and qualitatively analyzed (Osama, 2024). Incorporating citizen experience into digital twins enables more thorough and integrated analysis of cities via linking 3D features of physical space with human perception. This helps to better understand the urban space and can guide plans to improve the general user experience.
In this context, a study conducted by Wang *et al*. (2023) investigated the potential of leveraging Airbnb guest reviews to gain insights into urban characteristics. Hence, humans are conceptualized as sensors, with the detailed qualitative data embedded in textual reviews reflecting perceived urban qualities, such as transportation, amenities, sense of safety, and noise. Furthermore, Pham *et al*. (2025) in their research, use immersive virtual reality environments to simulate pedestrian experiences, enabling users to subjectively assess the quality of redesigned urban spaces. Vlugt *et al*. (2024) also proposes the Perceived Environment Walking Index (PEWI), which combines objective spatial data with user-reported perceptions, such as comfort, safety, and urban ambiance, to map discrepancies between physical infrastructure and experiential quality. Meanwhile, Kim *et al*. (2023) demonstrate that standardized metrics like Walk Score correlate weakly with lived experiences in Daegu, South Korea. They argue for the inclusion of qualitative indicators such as route safety, greenery, and slope conditions to better reflect user perspectives.

Lei *et al*. (2024) in their article demonstrated how crowdsourced perception scores, 3D morphology, and Google Street View imagery can be combined through hierarchical clustering and perceptual sub-clustering to enrich CityJSON features with human-centric attributes. In a related study, the same authors explored humans-as-sensors, where wearable devices and participatory sensing were used to model outdoor walking comfort within a functional campus-scale digital twin (Lei *et al*. 2024). Furthermore, Zarei *et al*. (2024) proposed a Social ADE that extends CityGML to structurally integrate public input, such as citizen comments, ratings, and environmental sensor data into urban models. Their framework formalized how qualitative human feedback can be semantically embedded in a 3D city model, using structured ADE modules validated through XML/XSD workflows.
Current efforts to integrate human data into UDTs remain limited in scope and tend to address specific use cases. The integration process is still in its early stages and has yet to evolve into a fully developed, standardized framework. While various tools and applications have been developed to support the collection of human data, often in innovative and technically sound ways, this data must be carefully processed, contextualized, and combined with objective spatial or environmental information to fully realize its analytical value. Without such integration, the data risks losing relevance and may remain underutilized. Together, the reviewed studies underscore a growing recognition of the need to systematically incorporate subjective human experience into UDTs. They contribute substantially to the advancement of human-centric UDTs by exploring avenues such as perception mapping, wearable sensing, participatory feedback, and predictive modeling. Nonetheless, they also expose common challenges, particularly in terms of interoperability, scalability, and the dynamic use of human input in urban analysis and planning. Furthermore, human perception represents a broad and intricate field of study, encompassing a wide range of cognitive, emotional, and contextual dimensions.

To support the meaningful integration of human perception into Urban Digital Twins (UDTs), it is essential to identify appropriate ways of linking 3D urban elements with perception data. In this regard, Jeddoub *et al*. (2024) explicitly identified three levels of data integration commonly used in Urban Digital Twins, based on real-world implementations at the urban scale : The first level, the Conceptual Data Model (CDM), which is based on structuring data and relationships through models such as CityGML, often extended using Application Domain Extensions (ADEs). The second level, the database level, focuses on adapting data to existing schemas without modifying the conceptual model, typically through ETL processes. Finally, the front-end level (client side) enables the integration and visualization of heterogeneous data through user interfaces such as dashboards, geoportals, and web-based 3D environments, often relying on technologies like CesiumJS.

Beyond these technical levels, advancing toward human-centric UDTs requires engaging with the

complex and multidimensional nature of human perception. Addressing these layers of complexity is essential for developing a deeper and more accurate understanding of how individuals perceive urban spaces, and for ensuring that such insights are effectively reflected within UDTs. At the same time, particular attention must be given to the role of citizens as primary providers of sensitive personal data, including activity patterns, opinions, and everyday behaviors. The use of such data introduces important ethical challenges, especially in relation to privacy and fairness (Qanazi *et al*., 2025; Q.-C. Wang *et al*., 2025).

II. MATERIALS AND METHODS

Building on the identified research gaps, particularly the limited integration of human perception in Urban Digital Twins (UDTs), this study proposes a methodological framework to incorporate perception data into their spatial context. The approach, including its tools and workflow, is applied and tested through a case study on Sart-Tilman Campus at University of Liège, which offers a controlled yet representative environment, characterized by a stable population and concrete issues related to quality of life.

A. Study Area and Use Case

1. Study Area

The study was conducted along a pedestrian route within the University of Liège campus in Liège, Belgium. The campus provided a controlled setting for experimentation, featuring a relatively stable population and well-defined challenges related to urban quality of life. The selected route was intentionally chosen for its spatial diversity and consists of three contiguous segments, each reflecting distinct urban environments and experiential characteristics.

- Segment 1 (S1): A green corridor and forest path offering a natural atmosphere (Figure 1a).
- Segment 2 (S2): The Allée du Six Août, a dense area marked by vehicular traffic, pedestrian flow, and the presence of academic departments (Figure 1b).
- Segment 3 (S3): Rue du Sart-Tilman, a residential street (Figure 1c).

2. Use case

Within the scope of this research, the urban dimensions addressed through human perception are conviviality and urban pollution. These two dimensions are defined as follows:

- Conviviality:

It is a fundamental concept that describes the qualities of urban public spaces that promote social interaction and human well-being (Thombre et al. 2020; Shedid et al. 2021). For the purpose of our research, we have reviewed the literature and determined the most frequently used factors in terms of urban conviviality. As a result, we will focus on the following seven key factors: Safety, Walkability, Social Interaction, Accessibility, Comfort, Places to sit, and Aesthetic Quality of Space (Figure 2).

- Pollution:

Urban environments are increasingly affected by multifaceted forms of pollution, notably noise, visual, and air pollution, which collectively degrade the quality of urban life and public health. That is the reason why we have focused on three forms of pollution: air pollution, visual pollution and noise pollution (Figure 2).

Conviviality and urban pollution were chosen as the primary dimensions of perception due to their multifaceted complexity and their role in shaping the lived experience of urban environments. These two concepts capture the duality of urban life, one reflecting comfort, sociability, and well-being, the other expressing discomfort, health concerns, and environmental stress. By using human perception as a lens to evaluate them, we move beyond objective and technical indicators to embrace a more subjective, citizen-centered understanding of urban spaces. This not only enriches the descriptive power of digital twins but also makes them more useful for decision makers seeking to design cities that are not only smart, but also livable and inclusive.

B. Methodology overview

The research was structured around a two-phase methodology, implemented on the Sart-Tilman campus of the University of Liège. The two phases of the research are as follows:

1. **Data Collection (Phase I):** Identification of key factors, design of a field survey, and acquisition of both subjective and spatial data.
2. **Front-End Integration (Phase II):** Development of the web platform *UrbanSense* to process, analyze, and spatially contextualize and connect perceptual data within a 3D urban environment.

C. Phase I: Data collection

The objective of the survey was to collect the spatial data and the associated subjective data related to human perception. Hence, the survey was promoted via QR codes displayed across the campus and through targeted email invitations sent to campus users. It is important to note that the survey was conducted during the daytime, with participants selecting from a set of predefined time intervals. Upon confirmation of their selected time interval, each participant was accompanied by a member of the research team, who provided a brief explanation of the survey procedure, along with the objectives and purpose of the study. During the walk, however, the research team deliberately refrained from engaging in conversation with the participant, in order to allow them to form an independent and unbiased perceptual evaluation of the segments. The anonymization of participant data was ensured from the outset in compliance with the ethical guidelines of the University of Liège. In accordance with the requirements of the university's ethics committee,

Figure 1. a) First segment b) Second segment c) Third segment

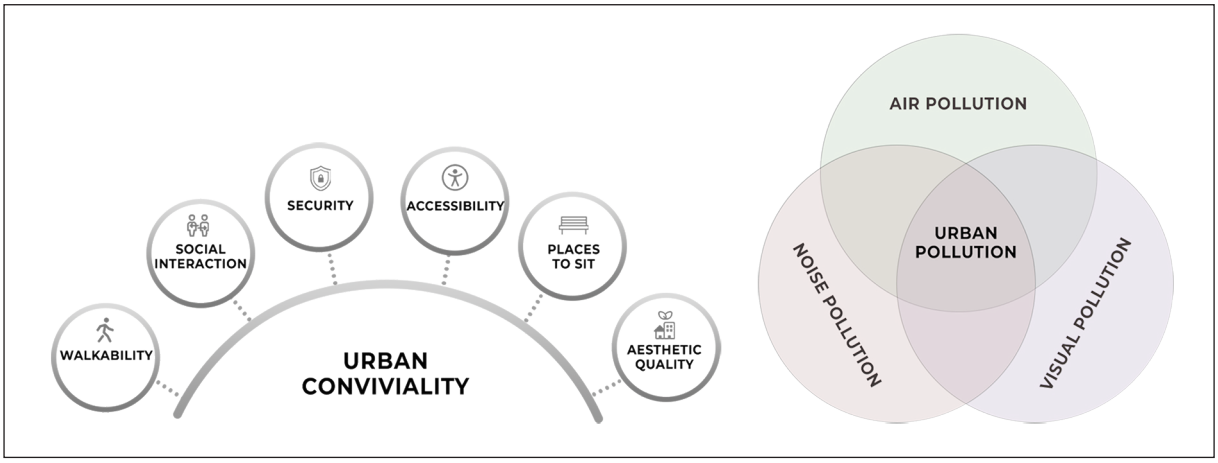

Figure 2. Conviviality and Urban Pollution dimensions

participants' informed consent was obtained, and all data were handled in a manner that guaranteed full confidentiality and security.

· Subjective data acquisition

Considering the definitions of conviviality and perceived pollution, as well as the various factors influencing each and the nature of the selected route, the questionnaire was carefully designed to reflect the project's objectives. Therefore, the ten key factors identified were translated into guiding statements to support participant understanding and ensure consistency in interpretation. These statements were designed to anchor participants' perceptions to tangible elements observed along the route. The formulated factors provide a structured framework for capturing the multifaceted nature of urban conviviality and pollution.

The survey responses were collected using a five-point Likert scale, ranging from "strongly disagree" to "strongly agree." This scale allows for the quantification and normalization of subjective perceptions into numerical values suitable for analysis. Given that the study area is divided into three continuous segments, participants were asked to respond to the same set of ten statements (seven related to conviviality and three to pollution) for each segment individually. An additional question was about how frequently participants use the segments assessed, the responses to this question were also on a five-point Likert scale ranging from "Never" to "Always".

The survey was implemented using the Microsoft Forms platform, a tool specifically designed for collecting information through customizable and anonymous questionnaires.

The responses were automatically recorded in an Excel file stored in the cloud via OneDrive, allowing the data to be downloaded in various formats, such as CSV.

· Spatial data acquisition

To enhance the scalability and reusability of the data collection tools beyond the scope of this case study, the data collection phase was designed to capture both subjective perception data and the corresponding spatial trajectories. The mobile application GeoTracker was chosen for this purpose, as it supports continuous GPS tracking in the background while allowing participants to simultaneously complete the perception survey. Compatible with both iOS and Android platforms, GeoTracker records the user's path and exports it in .kml format, which is interoperable with standard geospatial analysis tools. Upon completion, the recorded route is exported and appended to the corresponding survey response. Nonetheless, given that participants in this study followed a predefined and fixed path, the collected route data was not used in the subsequent methodological steps.

D. Phase II: Front-End Integration, development of the platform "*UrbanSense*"

Designed as a front-end interface, this web-based platform facilitates the processing and the integration of human perception data, gathered during the preliminary fieldwork phase, into 3D representation of the city, serving as a path toward the integration into fully designed UDTs. Its functionality includes processing raw input, aggregating data by segment, and linking it to the relevant geospatial context. The platform fulfills two primary objectives: to assess the effectiveness of perceptual data integration at this analytical scale, and to offer an automated mechanism for quantifying perceived levels of conviviality and pollution. A schematic overview of *UrbanSense* workflow is presented in Figure 3.

1. Platform architecture

· Architecture and Tools

UrbanSense is implemented as a single-page application (SPA) based entirely on front end technologies. CesiumJS handles 3D rendering, Chart.js supports data visualization, and core logic is executed locally via vanilla JavaScript. It was developed using a modular approach designed to incorporate human perception data within a 3D geospatial visualization framework. This architectural choice promotes separation of functionalities and supports scalability, ensuring ease of maintenance and the potential for future enhancements.

· Geospatial Data Configuration

The 3D scene incorporated a CityGML 2.0 dataset of buildings and trees developed internally. Following the methodology established by

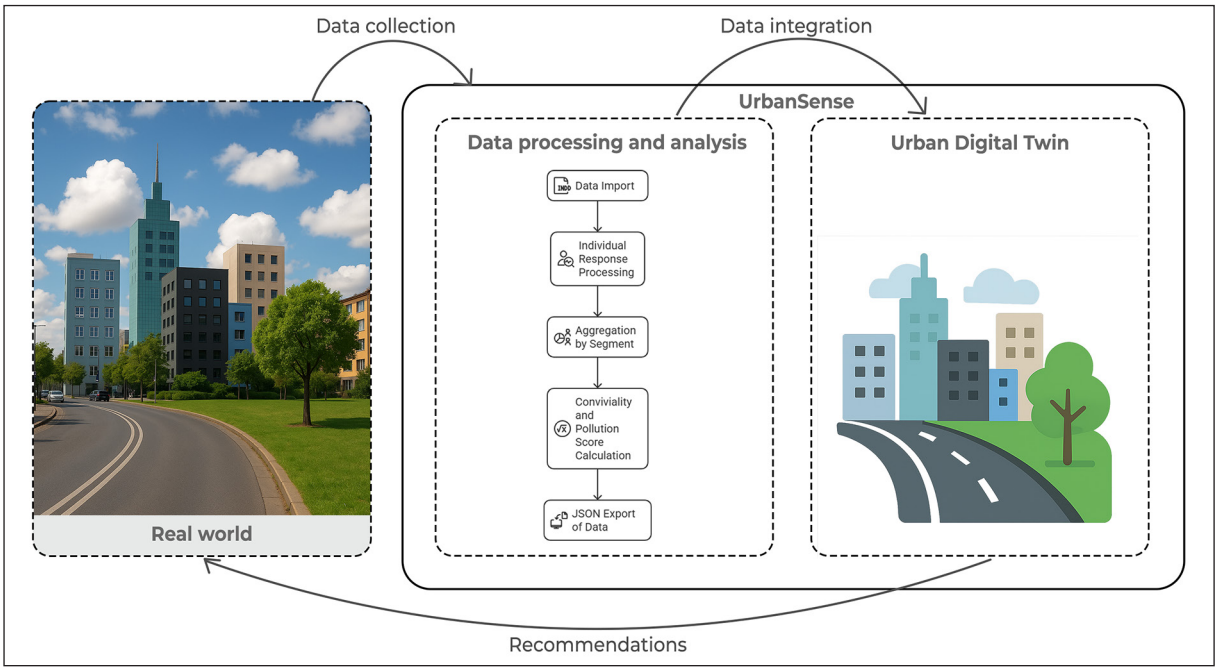

Figure 3. *UrbanSense* workflow

Ballouch *et al*. (2024), the building models were generated using the Geoflow pipeline, which integrates building footprints and LiDAR data to produce LoD 2.2 geometries. In accordance with the same study, tree models were derived from point cloud data combined with aerial imagery. The base imagery layer was sourced from OpenStreetMap.

The platform was additionally designed to import and visualize participant trajectories stored in .kml format. All spatial data were handled using the WGS84 geographic coordinate system.

· Perceptual Data Processing Pipeline

UrbanSense is developed to ensure an automated workflow raw data import, processing, normalizing, and aggregation. In order to fulfill this, the raw data once imported into the platform integrates a workflow as illustrated in Figure 4.

It is important to note that the conviviality factors were assigned fixed weights reflecting their relative importance in shaping urban conviviality. This relative importance was derived from a review of the literature, in which the most frequently cited factors were identified (Hosseini *et al*. 2024; Kim *et al*. 2023; Pham *et al*. 2025; Shedid *et al*. 2021; Vlugt *et al*. 2024). The resulting weights are therefore heuristic and exploratory in nature, adopted for the purpose of validating the proposed integration framework rather than for establishing definitive perceptual rankings. The weights were subsequently normalized to ensure that their sum equals 1, allowing for interpretable aggregation of factor contributions.

For perceived pollution, the assessment is based on three dimensions: noise, air, and visual pollution, which were considered to have comparable influence on the perception. Accordingly, equal weights of 0.33 were assigned to each dimension, resulting in an approximately normalized total weight of 0.99 (≈1).

· Data integration at the front-end level

Data integration in urban digital twins can occur at three distinct levels: the conceptual data model level, the database level, and the front-end level (Jeddoub *et al*., 2024). In the scope of our research, we opted to implement integration at the front-end level, which was realized through the development of *UrbanSense* platform. This integration relies on the combined use of CesiumJS and Cesium ion. CesiumJS enables the rendering of terrain, imagery, and 3D models. Cesium ion complements this framework by offering cloud-based services for the conversion, storage, and streaming of spatial datasets. Formats such as CityGML can be uploaded and transformed into 3D Tiles, a format optimized for efficient rendering in CesiumJS. These tools form a robust solution for developing

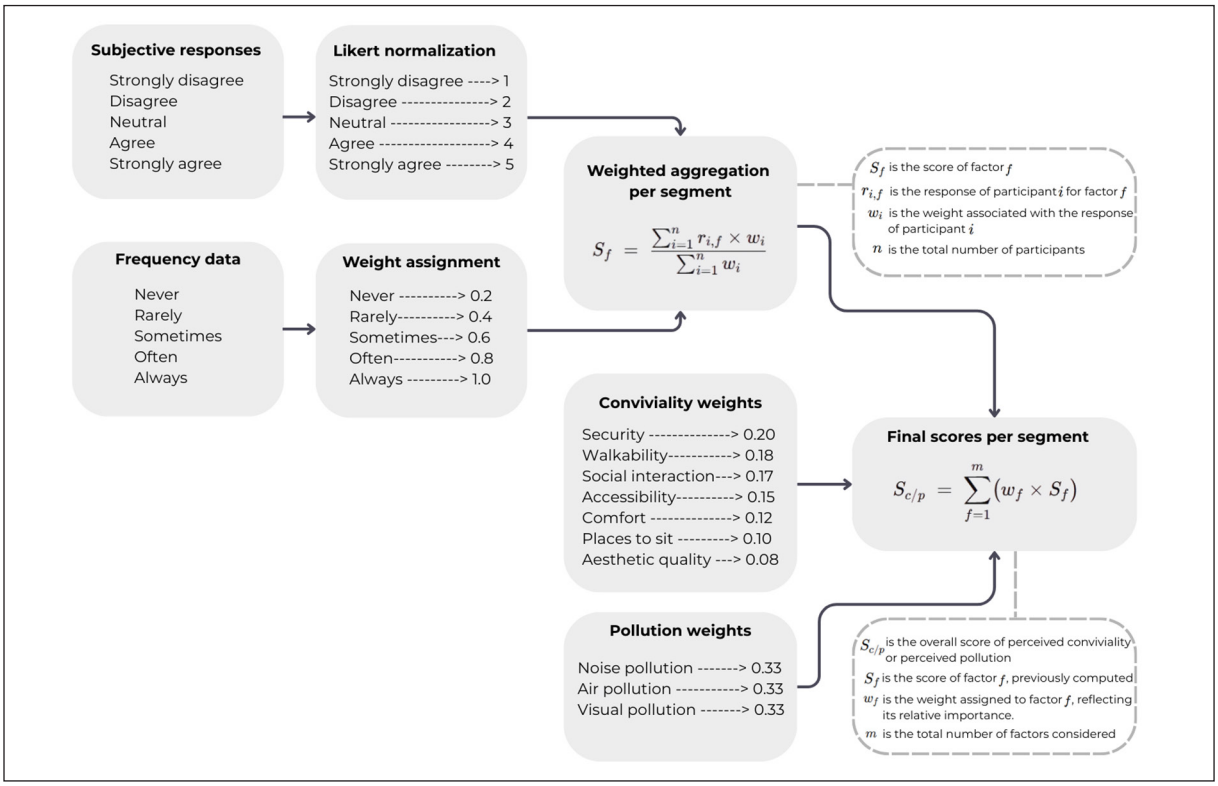

Figure 4. Methodological framework for quantifying perceived conviviality and pollution using perception data

lightweight, browser accessible applications, as exemplified by *UrbanSense*.

Accordingly, this third level (front-end level) of integration is implemented in two main steps:

1. The first step, conducted during the .CSV file import process, involves determining which segment of the route each participant has evaluated. In the dataset, each response includes a numeric reference (1, 2, or 3) that corresponds to a specific spatial segment of the predefined path. As the .CSV file is parsed, the system interprets these references to assign each response to the appropriate segment. This categorization enables the perception data to be systematically organized according to spatial divisions.
2. This step involves associating the processed perceptual data with its corresponding spatial segment. When a user selects a segment by clicking on its designated button, the system responds by automatically adjusting the camera view to center on the relevant area. The click event is detected through an event listener, which retrieves the associated segment ID. This triggers a zoom-in operation that repositions the 3D scene to focus on the selected geographical segment and visually highlights it within the interface. Simultaneously, a sidebar appears, displaying the perception data linked to the chosen segment, thereby reinforcing the spatial-contextual relationship.

I. RESULTS AND DISCUSSION

The following section presents and discusses the results obtained across the different phases of the study. For each phase, the key findings are detailed alongside a critical examination of the methodological and technical challenges encountered during implementation.

A. Data collection

1. Results

The survey was conducted at various times of the day, primarily between morning and late afternoon. A total of 13 campus users participated, providing their perceptions of the area. On average, each participant completed the survey in approximately 9 minutes. The data collection extended over several days, resulting in a temporally diverse dataset. Most responses were recorded during typical daytime hours, which reinforces the

contextual relevance of the perceptions gathered, particularly in relation to daily commuting patterns and campus activity cycles.

Each participant evaluated the three predefined segments of the urban route. All responses were automatically recorded and subsequently exported in .CSV format for analysis. The survey was conducted anonymously; no identifying information was collected. In accordance with the requirements of the university's ethics committee, participants' informed consent was obtained, and all data were handled in a manner that guaranteed full confidentiality and security.

2. Discussion

The decision to gather data on-site, within actual urban environments, offers a strong advantage for this stage of research. It aligns with the main objective: incorporating real human experience into UDTs. While virtual tools such as interacting with 3D models, virtual reality, or augmented reality, offer some insights, they tend to fall short. They often miss the complete range of sensory and emotional cues that come with being physically present in a space. Factors like surrounding noise, social interactions, changing light, and unexpected interruptions are all hard to replicate outside the real world. By conducting the survey in real time and within the actual environment, participants were able to respond to what they saw, heard, and perceived at that moment. This gives the data a level of authenticity that simulations usually can't reach.

Although the sample size (n = 13) may appear modest, it was appropriate for the objectives of this research. It enabled validation of the proposed integration workflow and provided a sufficiently diverse range of perceptions to characterize the three spatial segments under study within a proof-of-concept framework. Nevertheless, this limitation should be addressed in future studies through larger and more representative samples.

B. Phase II : Front-end integration

1. Results

This phase of the project was operationalized through the development of *UrbanSense*, which operates using two main input elements: a .CSV file containing the perceptual data collected during the on-site survey phase, and a set of .kml files representing the spatial segments assessed by participants. These inputs are processed through the automated workflow outlined in the previous section (2).

The platform delivers four key functionalities:

1. Visualization: Aggregated perceptual scores for conviviality and pollution are linked to their corresponding urban segments. The interface uses modal sidebars that display segment-specific metadata (e.g., name, participant count) and the overall perception scores (Figure 9a).
2. Detailed analysis: The sidebar displays aggregated scores for each contributing factor. A radar chart, generated using Chart.js, visually represents the factor scores, illustrating their influence on the overall assessment of conviviality and pollution for the selected segment (Figure 9b).
3. Comparative analysis: The Global analysis functionality generates a combined line chart that compares the overall conviviality and pollution scores across all three segments, allowing users to identify spatial disparities in perceived quality (Figure 9d).
4. Recommendations: A threshold-based recommendation system interprets the aggregated scores and provides targeted suggestions for improvement. Segments with conviviality scores below 3.0 out of 5 are flagged for enhancement, while pollution scores exceeding 3.5 out of 5 trigger intervention suggestions (Figure 9c).

An additional functionality is that all processed data, aggregated scores, and statistics (e.g., participants per segment) are compiled and exported as a structured JSON file for interoperability and further analysis (Figure 9e).

A summary of the inputs-outputs of the platform is shown in Figure 5.

The user interface was designed to be user-friendly and intuitive. To prevent visual clutter and maintain focus on the map, the interface relies on modal side bars that are contextually activated as needed. Figure 6 presents an overview of the initial interface displayed upon loading the platform.

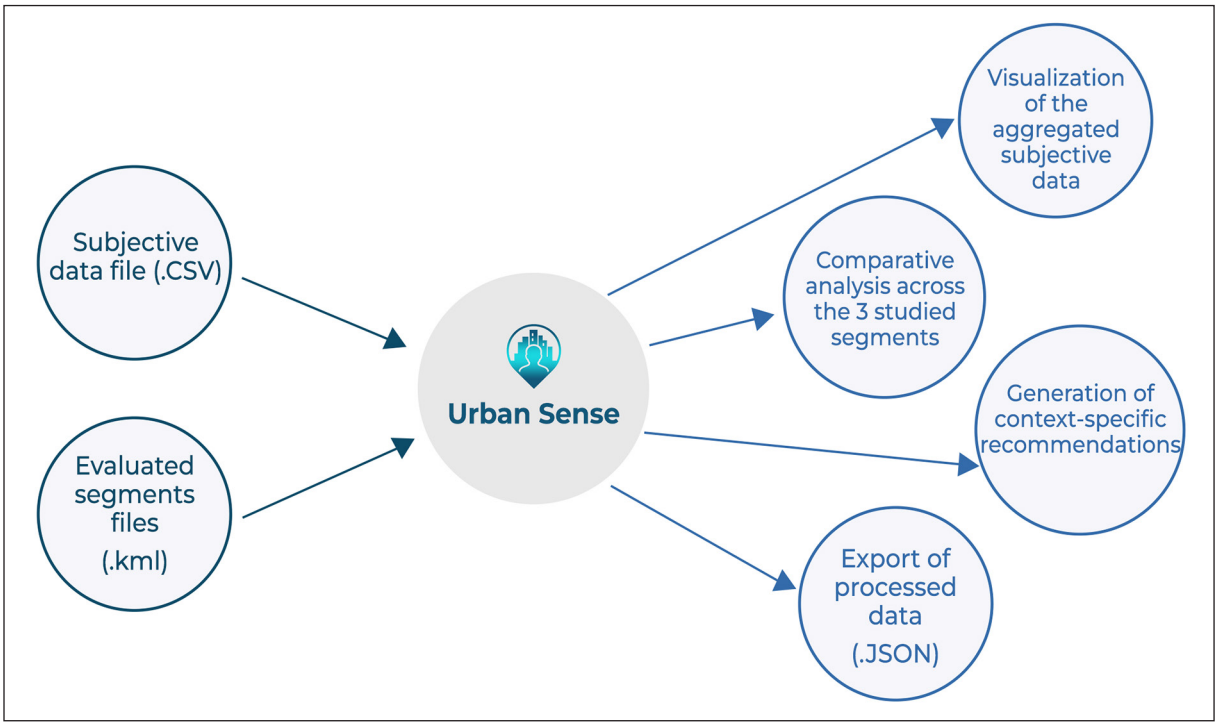

Figure 5. Summary of the inputs-outputs of *UrbanSense*

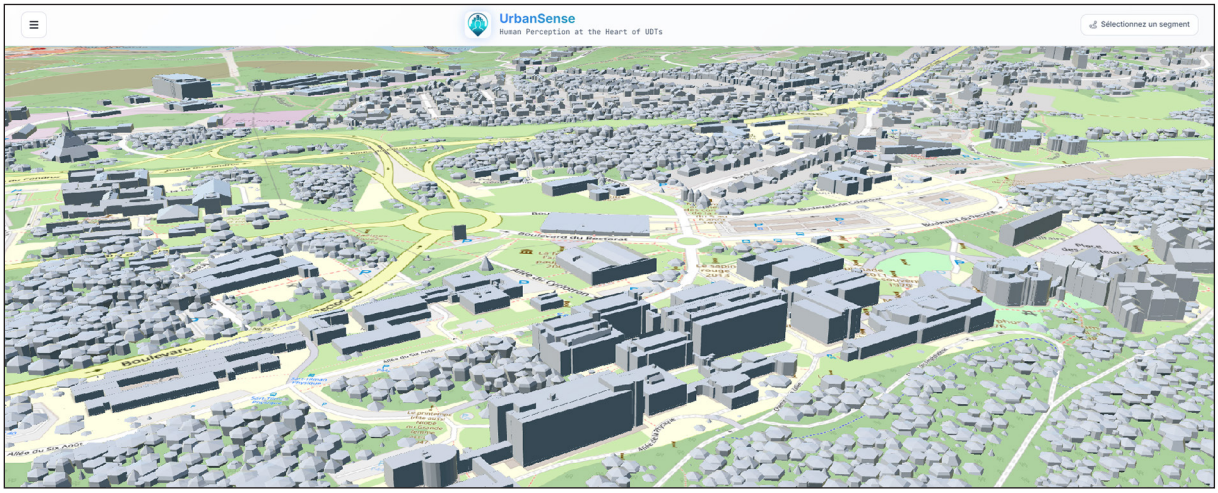

Figure 6. *UrbanSense* initial interface

Upon loading the platform, the interface automatically applies a zoom to center the view on the Sart-Tilman campus, using predefined geographic coordinates. The page loads in approximately 2s, ensuring a responsive user experience. The initial scene size is around 400 MB, which remains within an acceptable range for smooth and uninterrupted navigation within the 3D map environment.

As outlined in the methodology, the buildings are automatically loaded as 3D Tiles from Cesium Ion assets, along with their associated attributes. They are retrieved along with their attributes. When a user clicks on a specific building, a set of related information is retrieved and displayed in a dedicated information panel. An example of this functionality is illustrated in Figure 7.

To upload the input data, the user accesses the sidebar by clicking on the menu button. As illustrated in Figure 8, the menu is divided into two main sections: Data importing and Tools. The Data importing section includes two buttons that allow the user to upload the input files, the perceptual .CSV data and the corresponding .kml segments. The tools section provides additional functionalities, including options to export the

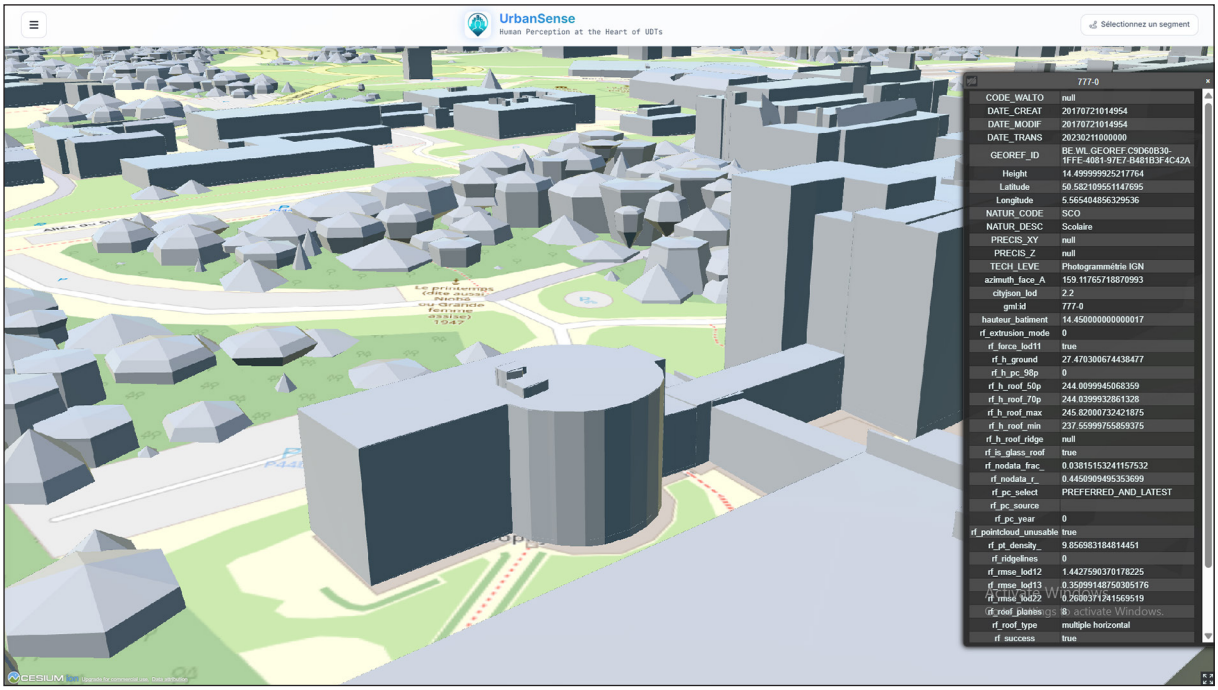

Figure 7. Displaying buildings information

processed data in JSON format, display the global analysis results, and generate context-specific recommendations.

After uploading the .kml files and the .CSV file, the spatial segments defined in the .kml are displayed on the map interface. Simultaneously, a dropdown menu is generated, listing the available segments along with a summary of their corresponding information retrieved from the .CSV dataset (Figure 9). By selecting a segment from this menu, the user can access its detailed perceptual data. This action triggers a modal sidebar on the right side of the screen and automatically zooms in on the selected segment within the map view. The sidebar presents key information regarding the segment's overall conviviality and pollution scores, as well as the aggregated scores for each of the contributing factors. These values are computed according to the procedure described in the methodology (refer to section I.D). To support visual interpretation, a radar chart (Figure 9b) is also embedded within the sidebar. This chart provides a comprehensive representation of the factor scores, illustrating their relative influence on the overall assessment of each perceptual dimension, conviviality and pollution.

The second key functionality of the platform is the comparative analysis of the three segments in terms of overall conviviality and pollution. This is accessed through the Global Analysis button, which generates a visual comparison between the segments. By contrasting the aggregated scores, the user can easily identify which segment is perceived as the most convivial or the most polluted. This comparison is rendered using a line chart developed with Chart.js, providing a clear and interpretable graphical overview of the differences across segments. An illustration of this feature is presented in Figure 9d.

Furthermore, the platform incorporates a threshold-based recommendation system (Figure 9c) that interprets the aggregated scores and provides users with targeted suggestions for improvement. For conviviality, segments with scores below 3.0 out of 5 are flagged for enhancement, prompting the platform to generate recommendations aimed at improving the aspects concerned. In contrast, for pollution, scores exceeding 3.5 out of 5 indicate heightened concern and trigger intervention suggestions to mitigate the identified issues. The recommendations are prioritized based on the severity of the scores, allowing users to focus on the most critical aspects within each segment.

Finally, the processed data are aggregated by segment and compiled into a structured JSON file, including the participants' perceptual data associated with each segment, aggregated scores, and summary statistics (e.g. participants

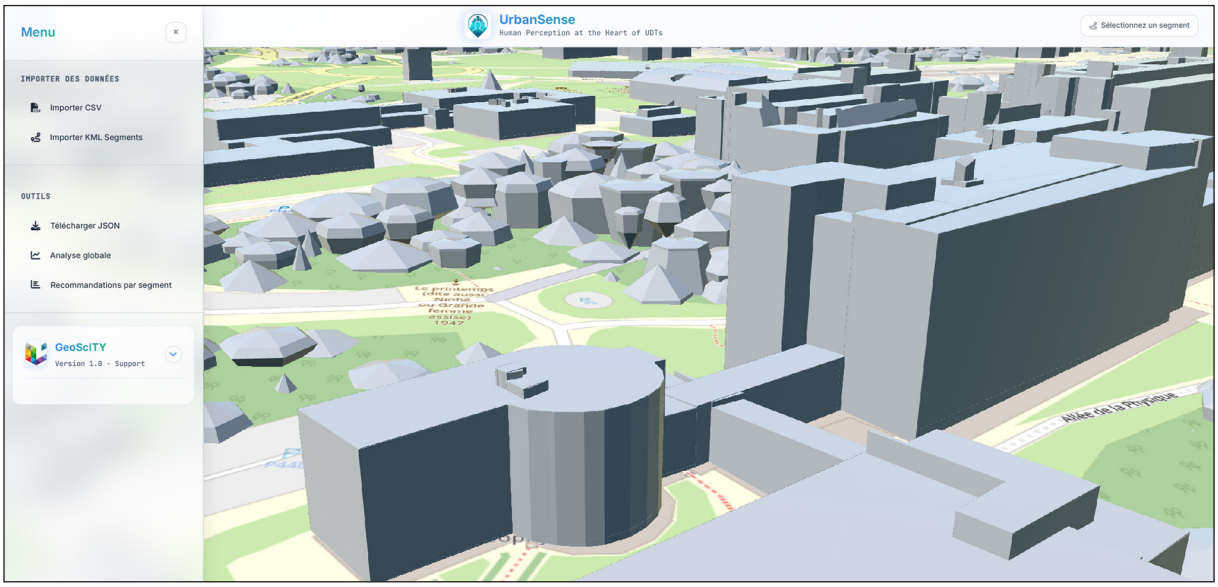

Figure 8. *UrbanSense* menu sections

per segment, average frequency of segment use). Additionally, metadata related to segment characteristics (e.g., type: residential, university, or forest) are included. This ensuring possibility for further use in other analytical workflows. A sample excerpt of the generated JSON file is shown in Figure 9e.

2. Discussion

In terms of analysis of the subjective data (Figure 10), the results derived from the survey data indicate that the most convivial segment is Segment 1, which corresponds to the corridor linking the Physics Department of the University of Liège to l'Allée du Six Août. This path is characterized by the presence of trees and natural elements, providing shade and a quiet environment that likely contributed to its high conviviality scores. In contrast, Segment 2 (l'Allée du Six Août) was rated as the least convivial. Despite being a central and dynamic part of the university campus, its functional nature and high foot traffic may reduce the perceived comfort of the space. With respect to perceived pollution, Segment 2 also received the highest pollution scores, reinforcing its role as a busy and potentially less pleasant environment. On the other hand, Segment 3, which traverses a quieter residential area, was rated as the least polluted. The recommendations section shows that, to improve the conviviality of the second segment, the focus should be on adding benches where people can sit. It is also important to enhance the overall comfort of the area, for example by introducing shaded zones. As for pollution, noise pollution emerges as the most critical issue, which is relevant given that the area is a dynamic route frequented by buses, cars, and pedestrians.

In terms of data integration, in this research, the integration of human data into the front end of the UDT was tested and validated. The interface of the platform was enriched with subjective data by linking each spatial segment to the perceptions collected during the on-site survey. This linkage between objective spatial data and subjective human insight allows for a more nuanced understanding of the urban context in which perceptions were formed. It facilitates a multi-layered reading of the city, where spatial attributes and human experiences intersect.

The integration supports not only visualization but also interpretation. Through the embedded analysis tools, users can identify key issues reported by participants and draw preliminary conclusions about the lived experience of the assessed urban areas. However, one of the current limitations of this level of integration lies in its scope: the human data layer, while displayed within the UDT interface, remains external to the core data structure of the digital twin. The integration of human perception into UDTs is increasingly recognized as a cornerstone in shifting from purely techno-centric approaches toward human-centric urban modeling. While current integrations enable both visualization and interpretation, allowing users to identify issues raised by participants and draw

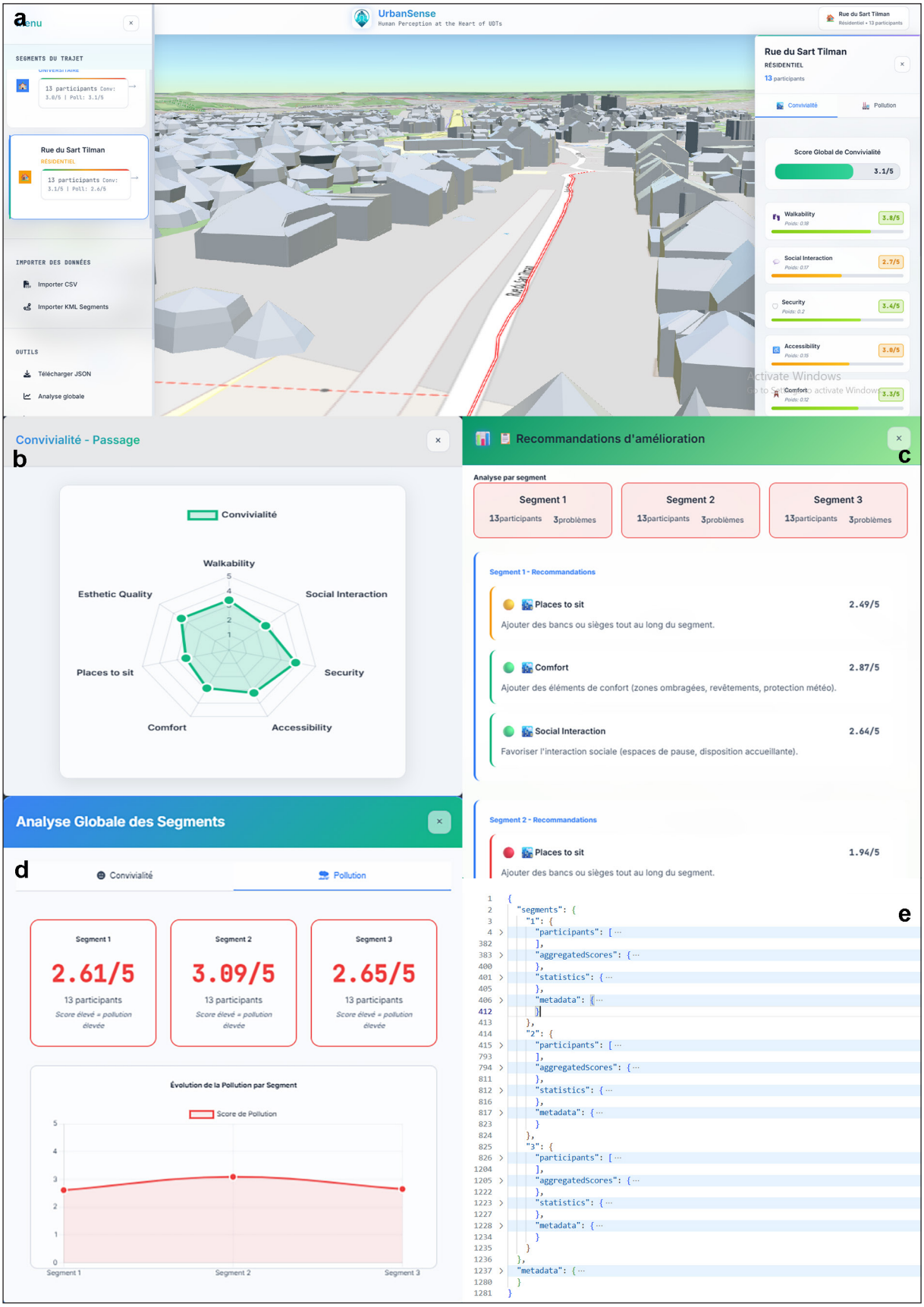

Figure 9. *UrbanSense* functionalities: a) Sidebar interface and segment visualization b) Radar chart visualization of conviviality factors c) Recommendations section d) Comparative analysis of segment scores e) Extract of the generated JSON data file

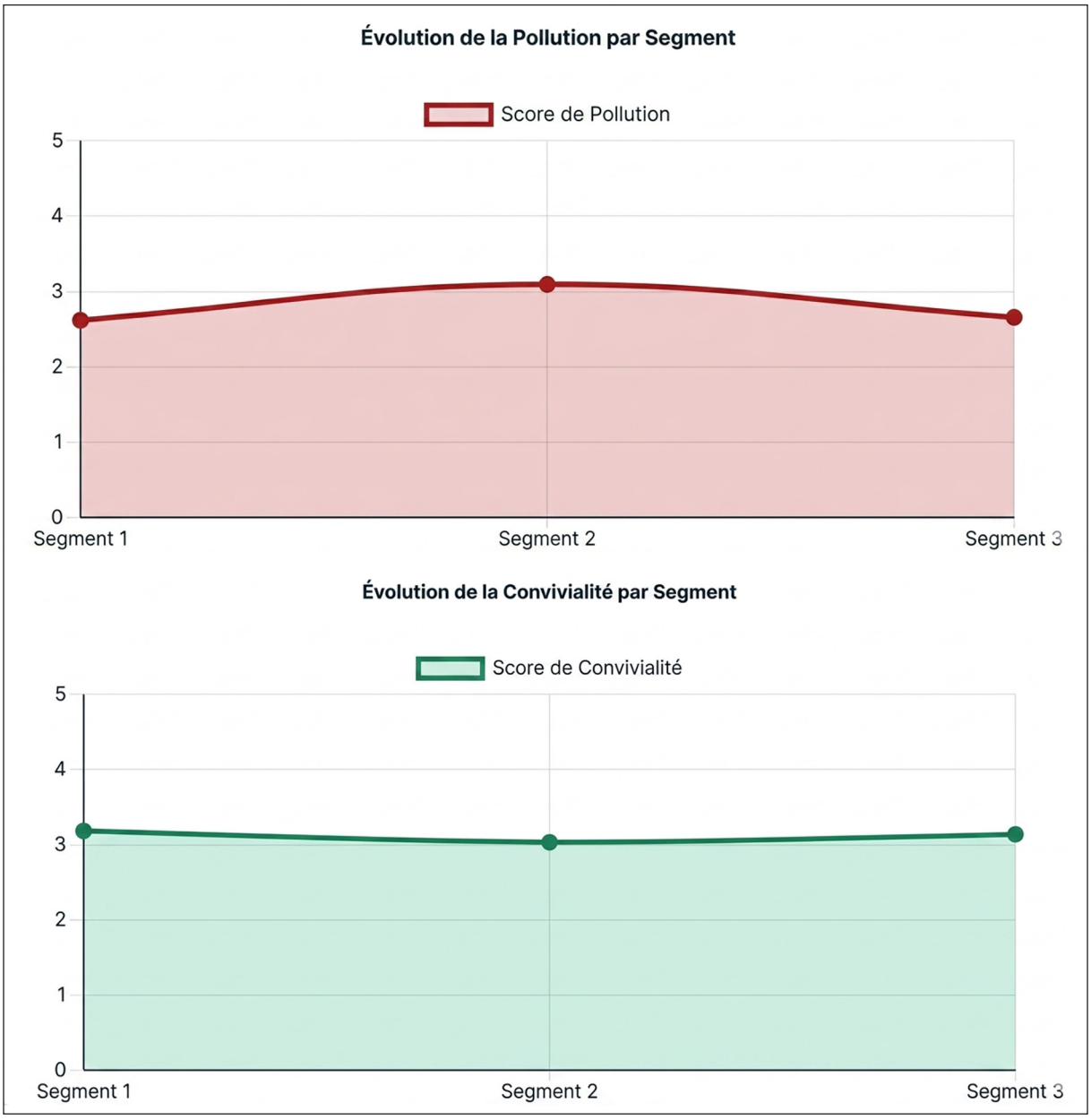

Figure 10. Global Analysis of conviviality and pollution

early conclusions about lived experiences, they often remain superficial. In most cases, perceptual data is visualized within UDT interfaces but exists outside the core data structures and native file formats that define the urban digital twin. This limits the potential for deeper analysis.

Despite promising developments, such integrations are frequently ad hoc and lack formalization. To meaningfully represent the complex relation between space, place, and human perception, a structured and semantically rich model is required. Rather than treating perception as an optional or additional data layer, embedding it within spatial ontologies and standardized city models would allow UDTs to capture cognitive, sensory, and experiential dimensions of urban life.

This raises a fundamental conceptual question: How deeply can human perception be integrated into urban digital twin? In the physical urban environment, human perception is not a peripheral layer, it is an element that co-constructs the city. Therefore, treating perceptual data as a mere visual layer risks overlooking its essential role in co-constructing urban space. *UrbanSense* offers a tool to process, analyze, and spatially contextualize perceptual data. It enables a meaningful first step toward human-centric modeling. Yet, results trigger the following question: how can this output,

particularly the perceptual scores, be further leveraged to support deeper semantic integration, where human cognition becomes an inherent and operational part of the urban digital twin?

CONCLUSION

Across the different phases of this project, the central objective remained constant: to explore how human perception data can be meaningfully integrated into UDTs, using a structured and multifaceted approach.

The adopted methodology stands out for its comprehensive structure, beginning with the collection of raw perceptual data, followed by its processing, and culminating in its front-end integration into a 3D city model. This incremental approach addresses a clear gap in the existing literature: although numerous studies have introduced tools for collecting human data, ranging from rating applications to VR-based interactions, few have established a comprehensive framework that spans from data acquisition to its integration within urban models.

By defining a study area and selecting conviviality and pollution as the use case, the project provided a practical framework to implement and test human data integration within UDTs. This choice was ambitious, given that both conviviality and pollution are inherently multifactorial and influenced by subjective interpretation. Nonetheless, it enabled a thorough exploration of how such dimensions could be structurally represented within a UDT environment.

The framework developed offers promising scalability. While our pilot focused on three segments within the Sart-Tilman campus, the same methodology could readily be extended across the entire campus or adapted to other urban contexts. The advances presented in this work are the result of a critical review of existing gaps in the literature, combined with an effort to push the boundaries of what UDTs can represent, particularly in terms of urban quality of life and human perception of urban spaces.

While the integration proposed here remains focused on two perceptual dimensions and a localized case study, it offers a solid foundation for further development. Future research could build on this structure to incorporate more complex behavioral data, support real-time updates, or integrate feedback loops between citizens and urban systems.

Building on the results of this study and the research questions it has raised, future work will focus on deepening the integration of human perception within UDTs, particularly at the semantic level. The objective is to move toward a model in which perceptual data are embedded from the earliest stages of urban digital twin conceptualization. Such an approach would ensure that human perception is not treated as a superficial or complementary layer, but rather as an intrinsic component of the 3D urban environment, contributing fundamentally to more human-centric, responsive, and inclusive urban models.

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