I.M.P.A.T.T.O. – Spatiotemporal GeoBigData and Predictive Models for Urban Planning and policies support in the Municipality of Udine

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ABSTRACT:

As urban centre face growing challenges from climate change, air pollution, and complex mobility patterns, city governments increasingly seek tools to plan more sustainably and act more responsively. Despite advances in urban sensing and data availability, most mid-sized cities struggle to integrate diverse data sources into a single platform for anticipatory decision-making. Moreover, traditional smart city approaches often lack citizen participation and educational value.

I.M.P.A.T.T.O. addresses this gap by designing and deploying an end-to-end urban intelligence system in Udine, a mid-sized Italian city known for its proactive environmental and digital policies. The project integrates mobility, environmental and presences data, low-cost environmental sensors developed by students. A web-based dashboard will be developed with predictive models that allow scenario-based planning and early-warning capabilities. Unlike many top-down initiatives, the system is co-designed by researchers, technicians, students, and municipal officers, allowing for long-term ownership and institutional integration.

In this paper, we describe the architecture, methodology, and operational model of I.M.P.A.T.T.O. We outline the key technologies used, discuss the participatory sensor deployment and educational modules, and present results from predictive modelling and dashboard integration. The paper concludes by discussing the alignment with international SDG frameworks and the potential for replication in other cities.

1. METHODOLOGY AND ARCHITECTURE

The I.M.P.A.T.T.O. system follows a modular architecture consisting of five integrated components: data ingestion and harmonization, participatory sensing infrastructure, predictive modelling engine, visualization dashboard, and civic/educational interfaces. This layered structure ensures scalability, interoperability, and adaptability to different urban environments and stakeholder needs.

1.1 Data Ingestion and Harmonization

Data integration in I.M.P.A.T.T.O. involves collecting and synchronizing real-time and archival datasets. These datasets available in phase one for the last 24 months are:

- presences and flows: from mobile phone data (TELCO). These data are divided by type of presence (residents, city users, regional, Italian, foreign) with their relative origins (municipalities for the Region, provinces for Italy and country for abroad) and are available for 1-hour time slots
- parking availability, provided by the company of the Udine Municipality that manages the parking lots; 2-minutes time slots
- meteorological data (rain, wind, humidity, temperature), three hours' time slots

During the second phase which will start approximately in autumn 2025 we will also have:

- bus access count, in and out for each bus stop
- air quality metrics: using the air quality measurement units developed using Arduino by Arturo Malignani students, technical high school in Udine, and which will be installed in the primary and secondary schools of the Municipality
- vehicular traffic counts, using video cameras that will be installed on the traffic lights of the main entrance routes to the centre of Udine
- bike sharing data, by the company that provides the bike sharing service for the municipality of Udine. These data contain the OD (Origin Destination) matrix of all the trips of the bikes.

A key innovation is the temporal alignment of datasets to a one hour interval and their spatial aggregation to the road network and the census section.

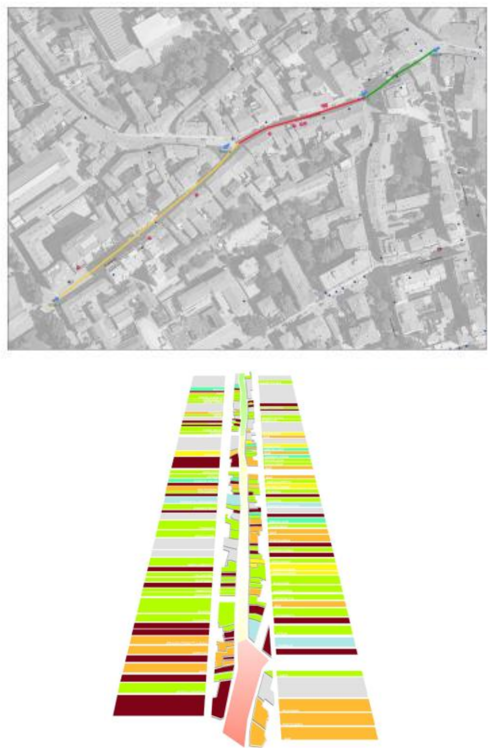

Figure 1. Two samples of Road Network characterization

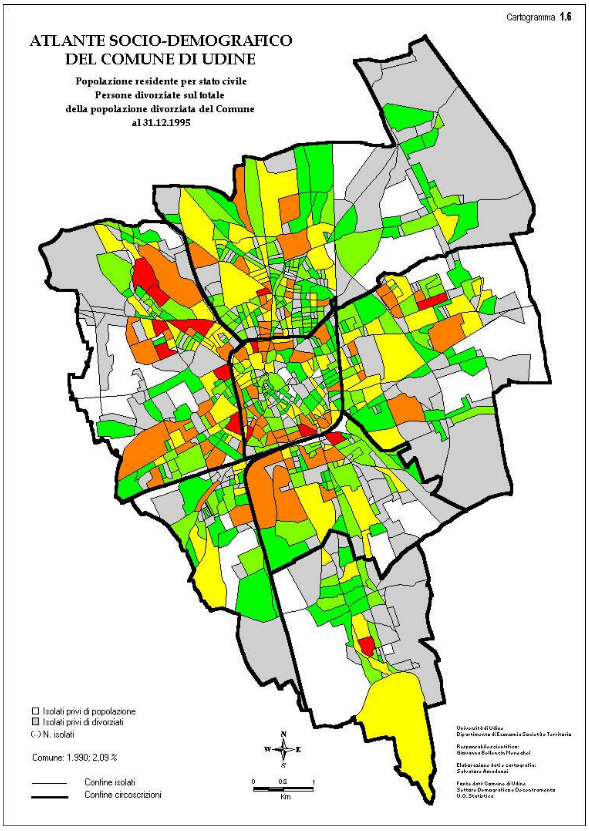

Figure 2. Census Sections map of the municipality of Udine

The goal of the municipality is to create an open data cloud to be used by the stakeholders.

1.2 Telco data

The Region Friuli Venezia Giulia has been buying for more than six years TELCOs data with one hour temporal granularity and municipality level spatial granularity (Amaduzzi 2023).
With this data base it's possible to obtain the number of people present divided by type:

- Resident: individuals who have predominantly spent their nights in the municipality over the last 6 months.
- City user: residents in other municipality who visit the selected municipality for at least 20 days a month (e.g., workers, students, etc.).
- Regional: residents within the region, with their municipality of origin.
- National: residents outside the region, with their province of origin.
- European: residents from European countries, with their nation.
- Intercontinental: residents from outside Europe, with their nation.

Additionally, the data can be further categorized by gender and age groups.

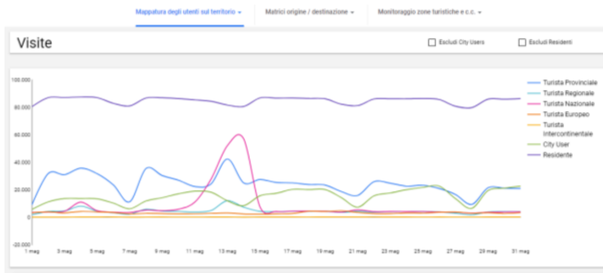

Figure 3. Daily distribution of the presences for the different cathegories

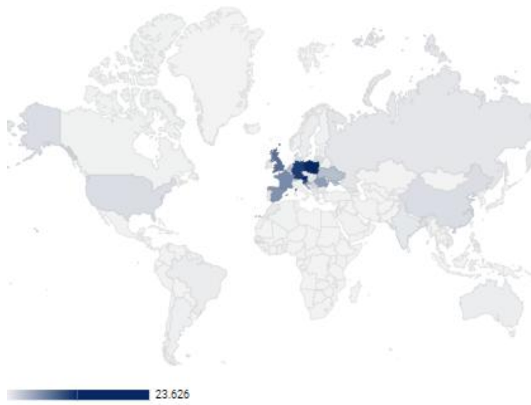

Figure 4. International presences map

1.3 Other data

Sistema Sosta Mobilità (SSM), the company owned by the municipality that manages the parking lots, has provided the database of the availability of parking spaces every 2 minutes for the last 3 years.

Figure 5. Parking in Udine

Meteo data (rain, temperature, wind, humidity) of the last 3 years at a one hour time granularity

00:00	poco nuvoloso	17.6°	assenti	5 NNE	94%	18.0°
01:00	sereno	17.4°	assenti	5 NNE	94%	17.0°
02:00	poco nuvoloso	17.1°	assenti	5 NNE	94%	17.0°
03:00	poco nuvoloso	16.3°	assenti	5 NNE	92%	16.0°
04:00	sereno	16.1°	assenti	6 NNE	90%	16.0°
05:00	sereno	15.9°	assenti	6 N	89%	16.0°
06:00	sereno	15.9°	assenti	6 N	87%	16.0°
07:00	sereno	16.8°	assenti	7 N	85%	17.0°
08:00	sereno	18.4°	assenti	7 N	84%	18.0°
09:00	sereno	20.2°	assenti	7 NNE	78%	20.0°
10:00	sereno	22.3°	assenti	7 ENE	73%	23.0°
11:00	sereno	24.3°	assenti	6 E	68%	25.3°
12:00	sereno	26.0°	assenti	6 ESE	63%	27.0°
13:00	sereno	27.5°	assenti	6 SSE	58%	28.6°
14:00	sereno	27.7°	assenti	6 S	53%	28.4°
15:00	poco nuvoloso	27.8°	assenti	5 SSE	53%	28.5°
16:00	poco nuvoloso	27.8°	assenti	4 SSE	54%	28.6°
17:00	poco nuvoloso	27.9°	assenti	4 SE	54%	28.7°
18:00	poco nuvoloso	27.9°	assenti	3 SE	55%	28.8°
19:00	poco nuvoloso	26.3°	assenti	2 ESE	55%	27.0°
20:00	poco nuvoloso	24.5°	assenti	0.9 ESE	56%	25.6°
21:00	parz nuvoloso	22.9°	assenti	1 E	62%	23.0°
22:00	parz nuvoloso	21.6°	assenti	2 E	69%	22.0°
23:00	parz nuvoloso	20.5°	assenti	3 ENE	76%	21.0°

Figure 6. Historic hourly meteo (temperature, wind, humidity)

1.4 Participatory Sensing Infrastructure

The sensor network is composed of approximately 50 air quality stations designed, assembled and deployed by high school students in Arduino environment.
Each station includes the following components:

- PM2.5 and PM10 sensor
- temperature and humidity sensor
- Wi-Fi-enabled microcontroller
- Solar panel and rechargeable battery for autonomous operation

These stations, deployed in the primary and secondary schools, send data to the municipality cloud where data is processed and made accessible through API.
Quality assurance includes validation against certified ARPA Friuli Venezia Giulia (FVG) stations, automated outlier filtering, and a calibration model adjusted monthly.

1.5 Visualization Dashboard

The predictive analytics component will use both statistical and machine learning models.
The web dashboard will be developed in order to enable:

- Real-time map display of all sensors
- Historical exploration of data by zone and date
- Custom visualizations for institutions and schools
- Download of time series in CSV and GeoJSON format
- Integration of forecast output and SDG-relevant indicators

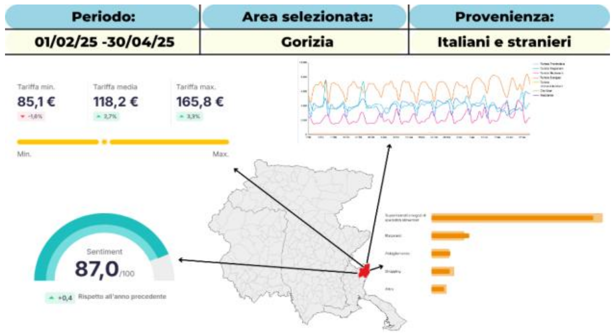

Figure 7. Sample of screen shot of the future dashboard

User roles will range from full administrative access for municipal technicians to public viewers who will explore data without login.

1.6 Educational and Civic Integration

Educational modules will be co-developed with teachers to align with curricula in environmental science, mathematics, geography, and informatics. Workshops will cover microcontroller programming, pollution science, data analysis, and ethical implications of monitoring.
Students will create reports, posters, and presentations that will be shared at city events, including the *Settimana Europea della Mobilità* and the local science fair.
Participating schools will receive open badges and IoT kits for future projects.

2. CLUSTERING AND URBAN PATTERN ANALYSIS

The period analyzed to date goes from 1/1/2022 to 31/12/2024.
We aligned all the data to a one hour interval
The goal was then to define and classify the various days and time slots so that, knowing the forecast for the following days, we could predict the likely situations that would arise. For example, if tomorrow is a mid-June Wednesday, with no events and rain is forecasted, we can predict, for the various time slots, attendance, parking availability and air quality. Consequently, decision makers can develop strategies to improve urban mobility and air quality, for example by reducing parking costs on the city's ring road or eliminating the cost of bus tickets for buses to the city centre from the park and ride facilities.
To classify situations, we have tested two different clustering methods. First of all we tested the K-Means Method.
The k-means method is a clustering algorithm that divides a data set into k groups (clusters) based on their similarity. It assigns each point to the cluster with the closest centroid (midpoint), iterating until the groups stabilize. We wanted to obtain 10 clusters, automatically. One clustering has been done for the entire period and another starting from the activation of the limited traffic zones.
A Limited Traffic Zone (ZTL) was established in the municipality of Udine on April 2nd, 2024. Only vehicles authorized by the municipality are allowed to travel within it.
One of the objectives of the analysis is to verify whether the introduction of the ZTL has positively impacted urban mobility and citizen services.
A second test is going on using Artificial Intelligence as a clustering tool. ChatGPT intelligence-based clustering uses the agglomerative method. Agglomerative clustering is a bottom-up, hierarchical approach that starts by considering each point

as a separate cluster and iteratively merges the closest pairs until a single final cluster is formed.
Each cluster of the K-Means Method has been analyzed in terms of explanatory features, helping identify distinct urban behaviour signatures. These signatures are used in downstream modelling and for scenario planning.

2.1 K-Means clustering first results

The first clustering was developed by organizing the data into the following time slots: 0-6, 7-9, 10-11, 12, 13-14, 15-18, 19-23, using the averages of the variables.
The application of K-means generated 10 clusters that were then analyzed, understood, and described.
Below are some examples of cluster descriptions that were very useful for understanding the different urban situations.

Cluster	Numero di elementi	Percentuale di ZTL	Posti liberi	Precipitazioni mm	Temperatura C°	Umidità%	Vento Km/h	Residenti	City user	Provinciali	Regionali	Nazionali	Europei	Intercontinentali
Cluster 1	677	49%	188,26	0,33	14,01	70,89	7,60	100510	20476	14576	3463	4215	2064	324
Cluster 2	394	6%	334,77	0,25	13,52	63,69	8,17	101240	8436	23225	2779	3979	1548	189
Cluster 3	728	23%	916,93	0,02	23,36	45,36	8,58	88232	4346	5514	1043	2457	1905	209
Cluster 4	846	9%	342,26	0,04	16,83	41,24	9,39	102700	17697	13682	2884	3216	1615	172
Cluster 5	1033	47%	916,45	0,24	16,45	81,28	5,74	99876	4695	4228	879	2687	2190	340
Cluster 6	580	95%	419,51	0,18	23,41	56,57	8,55	93965	10720	12332	2125	3644	3014	475
Cluster 7	675	10%	467,67	0,30	10,77	78,76	6,19	105420	18700	12709	2797	3368	1450	188
Cluster 8	828	9%	491,01	0,02	28,17	45,62	8,92	90478	8238	12704	1651	2643	2044	203
Cluster 9	698	9%	487,75	0,20	10,16	77,87	6,10	101880	8246	9111	1573	2992	1780	191
Cluster 10	1212	5%	966,40	0,14	7,25	81,88	5,40	106490	4407	3142	761	2211	1282	152

Figure 8. Synoptic of the clusters

In Figure 8 X-axis contains the list of the variables (attendance, weather, available parking, etc.) considered by the clustering algorithm, while the y-axis indicates the number of clusters.
The cells contain the average value of that variable for that cluster. The second column indicates the number of elements (time slots) that comprise that cluster. The third column contains the percentage of time slots of that cluster since the activation of the ZTL.
The colour of the cells represents the level of negativity (red) or positivity (green) of that factor for that cluster for the well-being of the city and citizens.
Below is an example of clustering interpretation for cluster number 3 which represents a set of situations characterized by:

- Ample parking availability: with an average of 917 free spaces, it is one of the clusters with the highest availability.
- Favourable weather conditions: almost no precipitation (0.02 mm), moderate temperatures (23°C), relatively low humidity.
- Time of year: predominantly summer and spring, particularly March-July (53%) and August (26%).
- Days of the week: weekends with a prevalence of Sundays (59%) and Saturdays (15%).
- Main time slot: 1:00 PM - 2:00 PM.
- Period of presence in the area: low numbers of residents and commuters; low local tourist flows, average foreign tourist flows.
- ZTL: present in 23% of cases.

And here is the interpretation we gave to this cluster: this cluster identifies urban low-pressure days during hot and dry weekends when much of the local population leaves the city (e.g., for day trips) and the city centre is empty, with few residents and not particularly high international tourism. Parking is therefore widely available.
For these reasons the suggested name for this cluster is “Quiet Summer Weekends”.
The municipal administration has validated these results and the next step of the project involves a reclassification as soon as we receive all the other databases (air quality, car passage counters, ...).

2.2 ChatGPT agglomerative method test

An initial clustering test was performed using ChatGPT. After providing the project document, the file containing daily data for all available variables, and a document describing the clustering objectives, we asked the user to propose 10 clusters using his agglomerative method.
The results seem very promising and quite consistent with those obtained and validated with K-Means.
This is one of the activities of the next phase of the project.

3. SCENARIO SIMULATION AND FORECASTING

Building on the clustering results and real-time data ingestion, the I.M.P.A.T.T.O. system includes a forecasting engine capable of simulating various urban scenarios. The goal is to provide local authorities with data-informed forecasts about events in the next few days taking into account the weather forecast and the time of year and the day of the week.

3.1 Forecast Models

The forecasting engine uses the clusters with inputs including meteorological forecasts day of the week, season, …and predicts event categories like "critical congestion" or "unsafe exposure" given a set of proposed conditions.

3.2 Scenario Input Variables

Users can modify input parameters via the dashboard simulation interface:

- ZTL activation schedules and perimeters
- Weather forecast assumptions (e.g. rain, wind speed, temperature)
- Special events (e.g. sport matches, street markets)

3.3 Outputs and Visualization

Forecast outputs include:

- Probability bands for PM2.5 and PM10 exceeding regulatory thresholds
- Estimated parking saturation levels by area
- Congestion risk by time and zone

Visual outputs will be rendered as maps with graduated colour, time series plots with shaded uncertainty zones, and textual summaries with SDG-relevant indicators (e.g., expected reduction in health exposure hours).
At this point, the decision maker can consider actions such as:

- tomorrow, parking along the Udine ring road will be free
- tomorrow, buses from the ring road to the city centre will be free
- ....

This information will be displayed on displays around the city of Udine, communicated by the media,

Figure 9. Road display

or notified via the SSM (company handling the parking lots) or Arriva Udine (local public transport) apps.

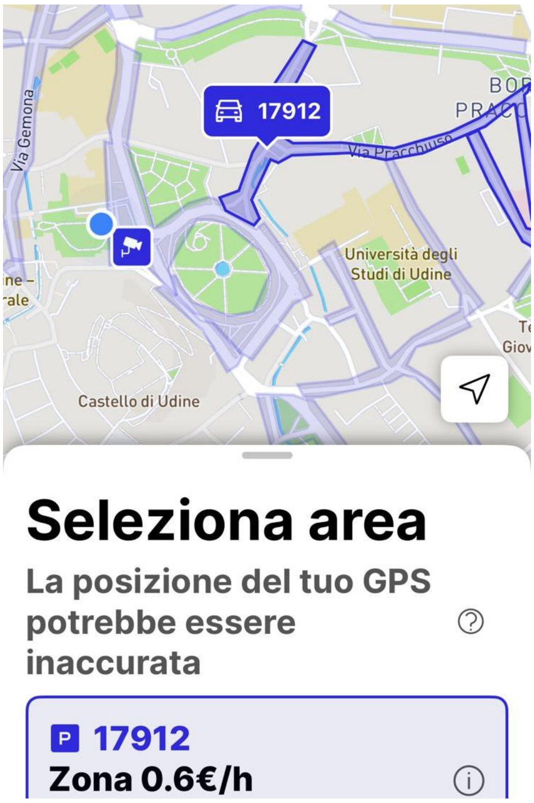

Figure 10. SSM app screen shot

4. IMPACT EVALUATION AND USE CASES

A core objective of the I.M.P.A.T.T.O. project is to measure the concrete impact of the data and modelling tools on municipal decision-making and urban conditions.
In this section, we outline the tools that decision makers could use to manage situations that negatively impact the health and services of those who frequent the city of Udine.
These initiatives were discussed with the Councilor for Urban Mobility, and they can be adopted at the end of the I.M.P.A.T.T.O. project (fall 2026), once all the information will be available, the clustering and the forecast dashboard will be certified.
It must be acknowledged that some of these initiatives could be very difficult to implement both due to bureaucratic/administrative issues and to the difficulties of acceptance by part of the population.

4.1 Use Cases in Urban Management

The forecasting tools and real-time dashboards will support multiple operational decisions:

- School bus rescheduling: forecasted PM10 peaks could enable the education department to modify school start times and reroute buses to reduce student exposure.
- ZTL enforcement calibration: activation hours could be adjusted based on predicted congestion clusters and air quality forecasts.
- Event planning: for public events in the city centre, simulations could guide traffic rerouting, parking management, and communication campaigns.

In each case, reports generated from the dashboard will be exported and attached to internal decision memos, ensuring traceability and improving future decisions.

4.2 Quantitative Metrics

Quantifiable improvements will be measured:

- Increase in use of open dashboard features by municipal staff over six months.
- Reduction in pollution exposure ($PM2.5 > 25$ µg/m³) in school zones during peak hours.
- Increase in use of the bike sharing.
- Reduction of the parking slot usage
- User sessions per month on the public dashboard.
- Uptime of the participatory sensor network over a 12-month period.

4.3 Institutional Integration

I.M.P.A.T.T.O. data and tools will be integrated into:

- The PUMS (Piano Urbano della Mobilità Sostenibile) monitoring system which is currently an ongoing project of the Municipality.
- Reporting for the Agenda 2030 Regional Strategy.
- Grant applications for environmental and digital innovation funding.

Hopefully in parallel, the project will lead to the creation of a permanent Urban Intelligence Unit within the municipal planning department, staffed jointly by city employees and university researchers.

4.4 Community Engagement Outcomes

On the civic side, over 350 students will take part directly in sensor assembly, coding workshops, or data analysis activities. We would like that some student-led projects be presented at regional fairs. A public campaign titled “Adopt a Sensor” will allow citizens to monitor, annotate, and compare data from sensors in their neighbourhood (Goodchild 2007).
We will prepare satisfaction surveys for participating students to understand if they have learned something useful for their future and have discussed of air quality issues at home as a result of their involvement.

5. BENCHMARKING AND COMPARATIVE MODELS

To learn and understand the positioning and uniqueness of I.M.P.A.T.T.O. in the broader European context, a benchmarking exercise was conducted against comparable urban data initiatives. This analysis helps identify both common methodological practices and innovative contributions introduced by the Udine model.

5.1 Comparative Projects

A review of six benchmark projects was carried out:

- OpenSenseMap (Germany): Citizen-built air quality sensors; strong open data strategy but limited in predictive analytics.
- SmartSantander (Spain): IoT-heavy infrastructure with minimal civic education or participatory sensing.
- CityAir (Italy): Mobile app-based citizen perception logging of pollution, without sensor calibration.
- AirQino (Tuscany): High-quality sensors, but cost and complexity limit scalability and educational deployment.
- Sensor.Community (EU-wide): Global open-source network of SDS011 sensors; lacks forecasting or institutional alignment.
- URBANITE (EU Horizon 2020): Big data integration for urban policy, strong in governance but lacking bottom-up sensor input.

I.M.P.A.T.T.O. distinguishes itself through its multi-layered integration of education, real-time sensing, forecasting, and institutional uptake.

5.2 Key Differentiators

- Educational co-production: Most projects lacked a structured integration with formal education.
- Forecasting and simulation: Only URBANITE had predictive elements, but none combined real-time forecasts with interactive dashboards and civic visibility.
- Cross-departmental integration: I.M.P.A.T.T.O. will influence transport, environment, education, and innovation departments jointly.
- Low-cost scalability: The system will be developed with commodity hardware, open data and open-source tools, ensuring replicability.

5.3 Transferability and Scalability

The modular structure of the I.M.P.A.T.T.O. platform has enabled early discussions with other municipalities in Friuli Venezia Giulia. Some municipalities have already declared their interest in replicating the project as soon as the first results are available.

Workshops will also be held with regional stakeholders to explore inclusion in the project financing strategy for public administration.

6. ECONOMIC AND ENVIRONMENTAL COST-BENEFIT ANALYSIS

A comprehensive evaluation of I.M.P.A.T.T.O. must include not only its technical feasibility and institutional adoption, but also its economic and environmental returns. This section presents a structured cost-benefit analysis covering direct expenditures, avoided costs, long-term benefits, and qualitative gains.

6.1 Initial and Operational Costs

- Sensor hardware and assembly: the participatory network of 45 sensors cost approximately €50 per unit, including the microcontroller, enclosure, and solar power. Total sensor infrastructure: €2.500.
- Software development: dashboard and backend platform developed in-house using open-source tools. Labor costs were shared across university research funding and municipal innovation staff. Estimated at €22,000 for the first 2 years.
- Training and education: workshops, guides, and coordination with 15 schools over two years: €5,000 (personnel, materials, badges).
- Hosting and cloud services: servers and storage for APIs, data, and forecasting models: €3,000/year.

6.2 Avoided Costs and Efficiency Gains

- Environmental early warnings: alerts on PM peaks will enable preventive measures, such as postponing school activities outdoors. There will be avoided cost in emergency logistics and communication.
- Optimized waste collection and street cleaning: using mobility forecasts to reschedule services will reduce overtime and fuel use.
- Grant acquisition support: we are sure that the project will be able to access ministerial and European funding.

6.3 Environmental Gains

- Due to the reduction of traffic and urban congestion we estimated high reduction of CO_2 through avoided vehicle km during traffic rerouting.
- Lower exposure in school zones will correspond to fewer hours of vulnerable exposure per month that will be evaluated using WHO air quality thresholds (WHO 2021).
- Citizen behaviour change promoted via dashboards and workshops will contribute to long-term modal shift and air quality awareness.

6.4 Long-Term Sustainability Model

To ensure operational continuity beyond the pilot phase, the Municipality of Udine is discussing a proposal:

- Budget line in 2026–2028 for system maintenance.
- Integration into regional PNRR-funded projects.
- Scaling partnerships with universities and civic groups for continuous monitoring.

These elements position I.M.P.A.T.T.O. as a financially and operationally sustainable urban intelligence infrastructure.

7. SDG ALIGNMENT AND POLICY UPTAKE

The I.M.P.A.T.T.O. project was designed not only as a technical exercise, but also as a strategic instrument to localize and operationalize the Sustainable Development Goals (SDGs) in urban policy. This section outlines how the platform contributes to measurable progress in several key SDG targets and how it has been adopted in institutional planning.

7.1 Alignment with Key SDGs

- SDG 11.6.2 – "Reduce the adverse per capita environmental impact of cities": I.M.P.A.T.T.O. provides real-time data on PM2.5 and PM10 at the neighbourhood level, supporting timely interventions and mitigation policies.
- SDG 4.7 – "Ensure learners acquire knowledge and skills needed to promote sustainable development": Educational modules in air quality science, IoT, and data literacy engage over 350 students.
- SDG 13.3 – "Improve education and institutional capacity on climate change mitigation": Through data-driven decision-making and citizen dashboards, the project fosters institutional responsiveness and community engagement.

- SDG 16.7 – "Ensure responsive, inclusive, participatory and representative decision-making": The project incorporates public feedback mechanisms and publishes data under open licenses.

7.2 Indicators Developed

Some of the custom indicators that we would like to derive from I.M.P.A.T.T.O. data streams are:
- Urban Wellness Index (UWI): composite of air quality, presence density, bike sharing usage, and green area proximity.
- School Exposure Score: PM2.5 exposure hours during school opening times per zone.
- Participation Score: number of dashboard interactions and feedback contributions per capita.

These indicators will be shared and discussed with the municipal decision makers and with Friuli Venezia Giulia Region Environmental Directorate for inclusion in the Regional SDG Monitoring Framework.

7.3 Replicability in National and EU Policy Contexts

The modular and open-source structure aligns with EU data spaces principles and the Green Deal digital priorities. The project will be submitted as a best practice to the "Premio per lo *Sviluppo Sostenibile* 2026" organized by the Foundation for Sustainable Development and *Ecomondo*-Italian Exhibition Group with the support of the President of the Italian Republic and was presented at the 2024 ISPRS Climbing for Climate GEOspatial school in Nepal.

8. HEALTH AND ENVIRONMENTAL IMPACT

One of the central motivations behind the I.M.P.A.T.T.O. project is its potential to improve public health outcomes through enhanced environmental monitoring and proactive policy-making. This section outlines the expected impacts on human health and environmental conditions in Udine.

8.1 Air Quality and Exposure Reduction

The participatory sensor network will provide high-resolution data on PM2.5 and PM10 concentrations across neighbourhoods, particularly in school zones. By cross-referencing these with time-of-day and presence data, the platform will enable targeted mitigation. For example:
- Schools will receive automated alerts during forecasted peaks above 30 µg/m³.
- The Department of Education and the Municipality will be able to reschedule outdoor activities.
- Local police will be able to modify traffic flow during events to reduce exposure zones.

The exposure of children to elevated PM levels (>25 µg/m³) will be drastically reduced if the municipality will use the dashboard and will be able to activate mitigation policies.

8.2 Awareness and Behaviour Change

The public dashboard will allow residents to monitor air quality near their homes, workplaces, and schools. Heatmaps, warning messages, and comparative tools will hopefully lead to changes in behaviour:
- Changes in commuting choices on high-pollution days.
- Parents modifying children's walking or biking routes to school based on dashboard data.
- Car users to use out of the ring parking slots and reaching the city centre with bus or bike sharing.

8.3 Environmental Co-benefits

While air quality will be the primary environmental focus, the project will very likely generate co-benefits in other domains:
- Noise mapping that will be supported by microphone-equipped sensors.
- Urban green planning will be informed by overlaying vegetation and pollution maps.
- Pilot studies on correlating humidity, heat stress, and PM retention will be proposed together with university departments.

8.4 Limitations and Ethical Considerations

While sensor placement was due to the school positions, socioeconomic disparities remain in sensor density. To address this in 2027:
- Additional units will be produced and installed in underserved areas.
- Citizens in all neighbourhoods will be invited to host sensors voluntarily.

GDPR compliance will be ensured, especially for presence data and school-level exposure indicators. No personal or device-level data will be stored or processed.

9. FUTURE SCENARIOS AND REPLICABILITY

The long-term value of I.M.P.A.T.T.O. lies in its adaptability, scalability, and integration into broader regional, national, and European frameworks for digital and environmental transformation. This section outlines forward-looking strategies for expanding the platform's technical capabilities and institutional reach.

9.1 Scaling to Other Municipalities

Preliminary discussions are underway with some municipalities in Friuli Venezia Giulia to replicate I.M.P.A.T.T.O. with localized configurations. Key steps include:
- Adapting data pipelines to local infrastructure and service providers.
- Installing school-based sensor networks using the Malignani model.
- Customizing dashboards with specific indicators of the local realities.

The modular codebase, based on open-source standards and RESTful APIs, allows deployment without proprietary dependencies.

9.2 Integration with Regional strategies

The FVG regional government is investing in technologies for planning and resilience. Our goal is I.M.P.A.T.T.O. to be considered for integration as a real-time environmental and mobility module. Benefits include:
- Live feedback between forecast models.
- Enhanced scenario testing for policy interventions.
- Interoperability with infrastructure, energy, and weather models.

9.3 Cross-Border Collaboration

Given Udine's proximity to Austria and Slovenia, cross-border pilots will be explored. These include:

- Shared forecasting models using transboundary weather data.
- Harmonized air quality alerts for commuters.
- Regional SDG dashboards using standardized indicators.

Funding opportunities could be the Interreg and Horizon Europe programs.

9.4 Long-Term Vision

By 2027, the goal is to transition I.M.P.A.T.T.O. from a project to a platform embedded within the city's digital infrastructure. This includes:

- Dedicated budget line in the annual municipal budget.
- Staff roles in the Urban Intelligence Unit made permanent.
- Creation of a regional observatory for digital resilience.

CONCLUSION

I.M.P.A.T.T.O. represents a comprehensive, replicable model of how mid-sized cities can leverage open data, civic engagement, and predictive analytics to promote sustainable, inclusive, and anticipatory urban planning. Through the integration of participatory sensing, real-time monitoring, and forecasting, the project will hopefully deliver both practical tools and cultural change in Udine.

Its success will surely lie not only in technical innovation, but in its grounding in educational and institutional partnerships. The platform is proving itself adaptable, cost-effective and impactful; attributes that make it an ideal candidate for scaling and policy alignment at national and EU levels.

As cities worldwide struggle with fragmented data systems, lack of public trust, and reactive policy cycles, I.M.P.A.T.T.O. offers a roadmap for building urban intelligence that is transparent, collaborative, and future-ready.

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