MAPPING LOCAL CLIMATE ZONES WITH MULTIPLE GEODATA AND THE OPEN DATA CUBE: INSIGHTS OF DOMAIN USER REQUIREMENTS AND OUTLOOKS OF THE LCZ-ODC PROJECT

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KEY WORDS: Local Climate Zone, Geospatial Data, Open Data Cube, Free and Open Source Software, User Requirements

ABSTRACT:

Rapid urbanization and climate change are intensifying the urban heat island (UHI) phenomenon across cities worldwide. There is a pressing need to implement evidence-based mitigation and adaptation strategies as well as to develop tools for effectively measuring the impact of such actions on UHI patterns. In this context, the Local Climate Zone (LCZ) concept is a well-established classification system commonly used for the assessment of UHI. With this in mind, we present here the LCZ-ODC project aiming to develop a methodology for LCZ mapping in the Metropolitan City of Milan (northern Italy) by leveraging multiple geospatial data and cutting-edge software tools, including the Open Data Cube (ODC). A key aim of the project is to develop user-oriented solutions facilitating the exploitation of the generated LCZ maps for different application tasks. In this paper, we first present a brief overview of the methodologies and data sources used in the literature for LCZ mapping. Then, we introduce the LCZ-ODC project, with a focus on the end-user requirements which were gathered through a questionnaire distributed to a sample of potential stakeholders. The primary objective of the survey was to collect insights and consolidate requirements related to the key features of LCZ maps that will be produced within the project. The outcomes of the survey play a pivotal role in guiding the project's development phase, ensuring that the project outputs will effectively address the identified end-user needs.

1. INTRODUCTION

Climate issues are nowadays among the most pressing societal challenges - recognized as priorities by the international community - due to their direct impact on human health and ecosystems (`https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health`). As climate change intensifies, the increasing frequency of heat waves and growing urbanization are exacerbating the urban heat island (UHI) effect in cities worldwide, with negative impacts on communities and the environment (Rizwan et al., 2008). The UHI phenomenon is recognized where the temperature patterns in urban areas are persistently higher than in the periurban and natural environment due to the modification of surface energy and radiation balance.

In view of the above, researchers have developed some approaches to measure the intensity of the UHI, which is the starting point to implement evidence-based adaptation and mitigation strategies (Deilami et al., 2018). In this context, the Local Climate Zone (LCZ) classification system has become a well-established framework to perform climate-related investigations (Stewart and Oke, 2012). The system defines 17 unique area types based on the physical and thermal properties of their surface which directly influence air temperature at screen height. Indeed, the logical structure of the LCZ system is well-supported by temperature observations and simulation results from surface-atmosphere models (Stewart et al., 2014).

LCZ maps are usually produced by leveraging multiple geodata (e.g. multispectral satellite imagery, topographic databases, and land cover maps) and following well-defined workflows (Aslam and Rana, 2022). However, state-of-art data and technologies leave large room for improvement. In addition, different characteristics in terms of map accessibility, format, and resolution may be demanded for different applications. This is the reason by which end-user requirements should be taken into account when designing the mapping workflow and choosing the final map features.

In view of the above, in this work we present the LCZ-ODC project between the Italian Space Agency (ASI) and Politecnico di Milano. The goal of the project is to produce multi-temporal and multi-resolution LCZ maps and analyze their correlation with air temperature observations by exploiting multi-source geodata and Earth Observation (EO) technologies. The study area is the Metropolitan City of Milan (northern Italy). The project's development exclusively relies on free and open-source software (FOSS). Specifically, the Open Data Cube (ODC) technology is leveraged for multi-source data integration and processing as well as the distribution of ready-to-use products for stakeholders and potential end-users.

With this in mind, in the present work we first provide a general overview of the methodologies and data sources that are most commonly used in the literature for LCZ mapping. We also outline the main application domains of LCZ maps. Secondly, we present the LCZ-ODC project by describing objectives, employed technologies, and expected outcomes, particularly focusing on user requirements. The latter were collected through a questionnaire distributed to a sample of stakeholders and potential end-users of the project outcomes. The aim of the questionnaire was to collect insights and consolidate requirements concerning the characteristics of the LCZ maps and software

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https://doi.org/10.5194/isprs-archives-XLVIII-1-W2-2023-581-2023

applications produced within the project. Accordingly, we present and discuss the survey results which will be used to improve the foreseen products and applications according to the user specifications.

The paper continues as follows. Section 2 describes data and methods used for LCZ mapping and the main application domains of LCZ maps. Section 3 includes an overview of the LCZ-ODC project. Section 4 describes the user requirements and discusses how they are addressed in the project. Conclusions and future work are reported in Section 5.

2. OVERVIEW OF THE LOCAL CLIMATE ZONE SYSTEM

The LCZ system was developed as a climate-centered classification to address the inadequacy of the simple urban-rural dichotomy for the analysis of UHI (Stewart and Oke, 2012). Classes are divided into 10 “built types” and 7 “land cover types” based on the surface structure (height and density of buildings and trees) and cover (impervious and pervious) (see Figure 1). The physical properties of each zone are measurable and nonspecific as to space and time. Accordingly, they can explain the contribution of urban surface features to heat fluxes (Anjos et al., 2020).

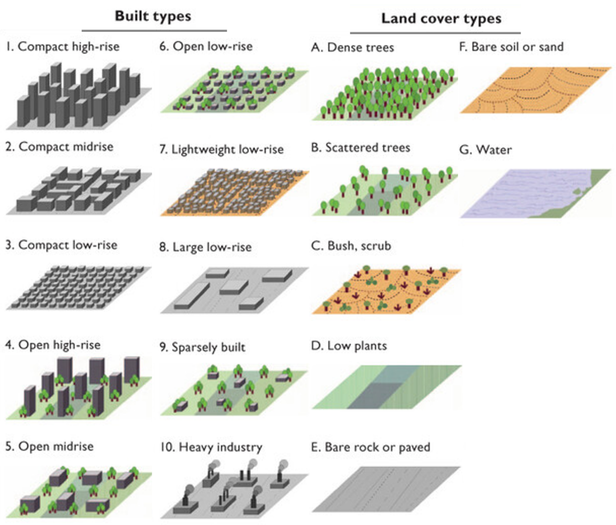

Figure 1. LCZ classification system (Stewart and Oke, 2012).

For the reasons explained above, LCZ maps are used in several application domains mainly connected with urban planning and UHI mitigation policies (Xue et al., 2020). For instance, LCZ maps are being increasingly exploited in studies related to outdoor thermal comfort (Liu et al., 2018), human health (Verdonck et al., 2018), carbon emission (Wu et al., 2018), and building energy consumption (Yang et al., 2020). Also, they can be adopted as a valuable tool for monitoring and modeling purposes, since they provide insights for improving meteorological sensor siting (Lelovics et al., 2014) while representing crucial inputs for atmospheric modeling at a local scale (Alexander et al., 2015). Researchers have also pointed out their potential usage in other applications connected with the UHI effect, including plant start-of-season (Meng et al., 2020) and air quality studies (Li et al., 2018).

Some approaches have been developed to produce LCZ maps. Remote sensing and Geographic Information System (GIS) based methods are mostly exploited (Aslam and Rana, 2022). Less frequently, approaches based on in-situ temperature measurements and urban climate models are also applied (Feng and Liu, 2022). The subdivision between remote sensing-based and GIS-based methods is primarily linked with data availability and accessibility. The former relies on the supervised classification of multispectral satellite imagery, having global coverage yet not providing sufficient required information (e.g. height of buildings) (Ma et al., 2021). The latter relies on the reclassification of multiple geodata which can provide the information needed for computing the urban canopy parameters (UCPs) defined in the original LCZ framework. However, necessary geodata is not always available and comparable in different urban contexts (Quan and Bansal, 2021). Combined approaches leveraging satellite imagery and ancillary data - such as building height and imperviousness layers - can be used to compensate for the limitations of the above methods (Fung et al., 2022). Combined approaches are also proposed to overcome any lack of detailed morphological and land cover data as well as improve the calculation sensitivity of remote sensing-based methods (Lehnert et al., 2021).

In this context, the World Urban Database and Access Portal Tools (WUDAPT) offers detailed guidelines on how to perform LCZ mapping and provides access to LCZ maps of different cities (`https://www.wudapt.org/`). WUDAPT provides an easy-to-understand workflow mainly relying on freely available data and software, thus representing a benchmark for LCZ classification. The WUDAPT protocol has been also applied to produce continent-scale LCZ maps, such as for Europe (Demuzere et al., 2019).

Regarding remote sensing-based methodologies, Landsat 8 imagery is widely suggested given its global coverage, medium spatial resolution, and data acquisition in both optical and thermal infrared bands (Bechtel et al., 2015). Sentinel 1 and 2 images have also been exploited in some research works, proving to be beneficial for multi-seasonal classification, training set configuration, and feature importance analysis (Aslam and Rana, 2022). Light Detection and Ranging (LiDAR) data have been used to obtain detailed urban morphology information such as building height (Bartesaghi Koc et al., 2018).

Supervised pixel-based classification algorithms are usually applied to obtain LCZ maps from satellite imagery. Algorithms exploited in the literature include Random Forest, Naive Bayes, Support Vector Machine, and Multilayer Perceptron, among others (Bechtel et al., 2016). Deep learning algorithms such as Recurrent and Convolutional Neural Networks have proved to remarkably improve classification accuracy (Yoo et al., 2020). Object-based classification methods have been tested as well, yielding promising results (Ma et al., 2021). Improvements in classification quality can be achieved by leveraging multi-source and multi-temporal optical data (Qiu et al., 2019) as well as ancillary geo-data (e.g. OpenStreetMap) that provides information on building height (Zhang et al., 2019).

Despite the advantages and good classification performance of remote sensing-based methods, some open issues may be outlined. These include the lack of a global high-quality training sample and concerns on the optimal mapping scale (Ma et al., 2021). Regarding the latter point, a spatial resolution of 100-150 m may be considered as a good compromise to express the context information of LCZ types (Bechtel et al., 2015). This is the reason by which satellite data and/or LCZ maps are sometimes down-sampled to lower resolutions (Ren et al., 2019).

https://doi.org/10.5194/isprs-archives-XLVIII-1-W2-2023-581-2023

On the other hand, GIS-based approaches rely on the definition of a basic spatial unit (BSU) - such as a lot area polygon or urban block unit - on which the UCPs are computed (Quan and Bansal, 2021). UCPs include both urban form and landscape parameters (e.g. sky view factor and aspect ratio) as well as thermal and radiative parameters (e.g. surface admittance and albedo), as defined in the original LCZ classification. Multiple geo-data are exploited for UCP computation and mapping, mainly building footprint and height data, road cover and land use/land cover maps, and Digital Terrain Models (DTMs) (Quan and Bansal, 2021). Additional data sources are topographic maps, aerial photographs, and satellite imagery (Unger et al., 2014). UCP maps are finally combined to obtain LCZ maps using standard or modified-standard rule-based classifiers (Wang et al., 2018), as well as fuzzy rule-based classifiers (Geletič and Lehnert, 2016).

GIS-based methods provide a straightforward framework for LCZ mapping. However, some challenges may be pointed out, including the availability of detailed datasets for UCP estimation, the classification of highly mixed areas, and issues related to the computation of UCP values and the definition of the BSU. Comparisons of LCZ maps obtained using remote sensing and GIS-based methods show a considerably varying agreement, thereby no general conclusion may be drawn (Quan and Bansal, 2021). The choice of the approach to be followed should first consider data availability and accessibility, thus depending on the case study.

With this background, the implementation of a standard and uniform methodology for LCZ mapping represents a meaningful objective for multiple applications of LCZ maps. Future research challenges should include the integration of multi-source geo-data for both LCZ mapping and ground truthing. The use of multi-resolution satellite imagery along with aerial photographs and building information can be beneficial for this purpose. Also, there is a need to boost multi-seasonal and multi-temporal LCZ mapping given the evolution of LCZ with the vegetative seasonal cycles.

3. THE LCZ-ODC PROJECT

Based on the literature summarized in the previous section, the LCZ-ODC project aims to develop an innovative methodology for LCZ mapping by leveraging multi-source data and state-of-art technologies for geospatial data management. The test-bed selected for the activities is the Metropolitan City of Milan (northern Italy). The project is funded by ASI in the framework of Innovation for Downstream Preparation for Science (I4DP_SCIENCE) Program. The project's primary objectives entail the production of multi-temporal and multi-resolution LCZ maps and the assessment of their correlation with air temperature measurements. The exclusive use of free and open-source software is a key paradigm of the LCZ-ODC project for both data processing and analysis (see Figure 2).

Specifically, the project takes advantage of high-resolution satellite imagery as well as local and regional geospatial layers. Satellite data include the hyperspectral satellite images from ASI's PRISMA (Hyperspectral Precursor of the Application Mission) mission and multispectral images from the European Space Agency Sentinel-2 constellation. Ancillary geodata such as the regional topographic database and land use/land cover maps are used as supplementary data for satellite imagery classification as well as training and testing sample construction. In

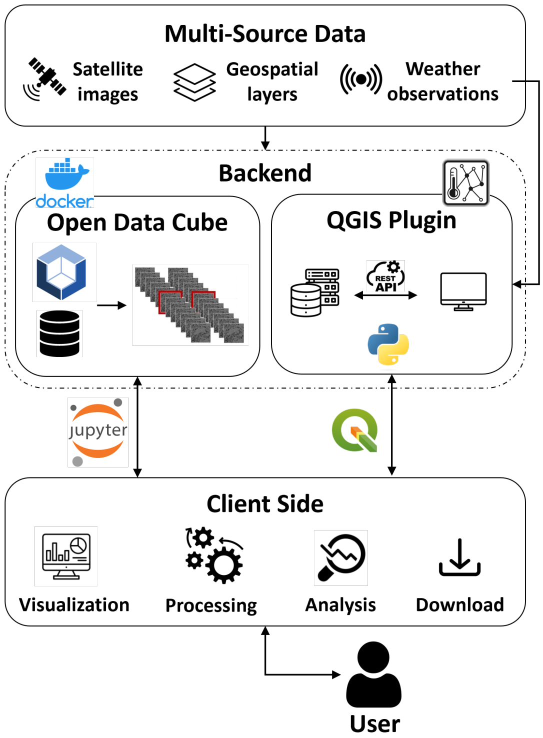

Figure 2. Schematic software architecture of the LCZ-ODC project.

addition, in-situ weather observations of the Lombardy Region Agency for Environmental Protection (ARPA) network are exploited for the correlation analysis between LCZ maps and air temperature.

The ODC is used in the project as a backend system for managing multi-dimensional and multi-temporal geospatial data with heterogeneous format and resolution in a single end-point (`https://www.opendatacube.org/`). This software provides access to structurally complex files that alternatively would require high expertise from the user. Accordingly, the ODC makes available ready-to-use data for the next stages of processing or analysis. The user can easily interact with the ODC using a standard interface, e.g. the Jupyter Notebook (`https://jupyter.org/`). This is a free and open-source coding tool that allows the user to access and query ODC datasets as well as display and interact with the outputs without re-running the code every time.

In particular, pre-configured ODC instance containing images and analysis-ready data - including multi-temporal and multi-resolution LCZ maps for the study area - will be published in a Docker container (`https://www.docker.com/`), equipped with libraries and tools needed for data processing and analysis. Jupyter Notebooks will be provided that contain documentation and ready-to-use code for interacting with the data contained in the ODC. This will also allow users to easily explore, manipulate, and export satellite imagery, maps, and related data from the ODC, streamlining the data analysis and exploration process. Furthermore, an experimental QGIS plugin will be developed to facilitate access and pre-processing of openly available data from ARPA Lombardia sensor network for their direct use in QGIS.

4. USER REQUIREMENTS AND PROJECT OUTLOOKS

The applications and products generated in the frame of the LCZ-ODC project need to achieve high levels of usability while fulfilling different end-user needs. For this reason, we carried out a survey targeting potential stakeholders and end-users of the project's outcomes with the aim of collecting users' feedback and consolidating their requirements. In this section, we present the survey results, explaining how user needs are addressed in the project development phase.

Stakeholders were identified among four main categories, namely (1) public administration, (2) university and research, (3) professionals and professional associations, and (4) foundations (Figure 3a). Professionals encompass engineers (40%), architects (30%), atmospheric physicists (10%), environmental biologists (10%), and communication responsible (10%) (Figure 3b). On the other hand, stakeholders coming from the public administration primarily belong to ARPA (Lombardia, Lazio, and Friuli Venezia Giulia) (60%), Regions (Toscana) (20%), and Metropolitan Cities (Milan) (20%) (Figure 3c).

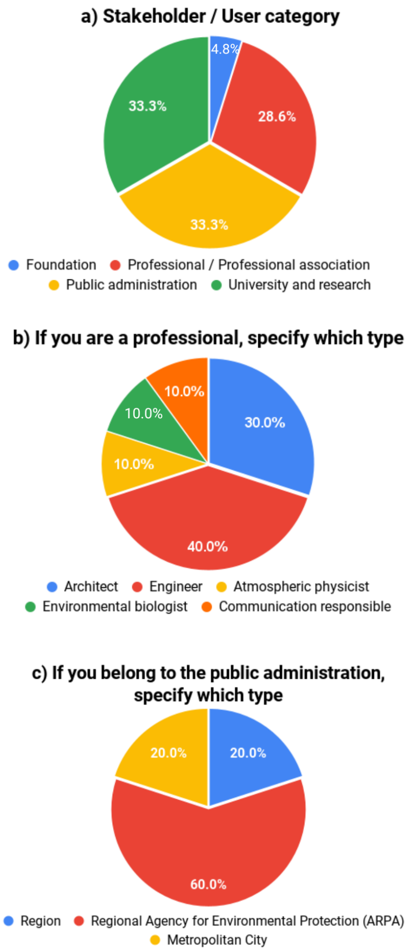

Figure 3. Overview of the stakeholders involved in the survey for the collection of user requirements.

Stakeholders were introduced to the project activities during dedicated workshops, wherein the project's expected outcomes were presented, and initial user feedback was collected through a round table discussion. User requirements were systematically gathered as downstream feedback through a questionnaire distributed among the workshop participants. The questionnaire aimed to collect information regarding stakeholders' prior usage of LCZ maps and the specific application context (e.g. software and models). Also, the questionnaire included questions about the potential application domains and desired technical features of the maps, such as spatial and temporal resolution, as well as format. Participants were also given the opportunity to provide additional information and remarks based on their own professional experience and work duties within open-ended questions.

Results revealed that most of the stakeholders (67%) had never previously used LCZ maps in their work (Figure 4a). Some of those who has already used them, exploited these maps for diverse applications, including (1) definition of site metadata for meteorological monitoring stations, (2) urban planning projects fostering nature-based solutions and climate change adaptation strategies, (3) educational activities, and (4) micro-climate analyses of the urban environment. A small portion of stakeholders (Figure 4b) employed LCZ maps for meteorological modeling applications, specifically exploiting WRF (Weather Research and Forecasting) and Ladybug models. Stakeholders who had not previously utilized such products expressed interest in the following applications (in order): (1) scientific research (e.g. applied climatology and UHI assessment), (2) professional activities (e.g. improvement of energy efficiency of buildings), (3) support to public administration tasks and workflows (e.g. development of climate change mitigation and adaptation strategies), and (4) urban atmospheric modeling (Figure 4c). These findings align with the typical application domains of LCZ maps illustrated in Section 2.

Regarding the desired characteristics of LCZ maps expressed by the stakeholders, the spatial and temporal resolution and ease in map access (possibly through an automatic pipeline) and management are the most relevant user requirements to be considered in the map production and distribution phases (Figure 5a). Indeed, an easy accessibility of the maps through dedicated platforms and friendly user interfaces may be beneficial for the activities connected with professional projects and public administration practices. This would allow end-users to easily exploit the project outputs for standard processing and operational routines.

More specifically, a medium spatial resolution is mostly required (43%); however, stakeholders also suggested higher (<30 m) and lower (>50 m) resolutions, in accordance with the different application purposes (Figure 5b). Similarly, various temporal resolutions were indicated, including seasonal (43%), monthly (38%), and yearly (9%) mapping frequency. In general, at least a distinction between winter and summer was required to properly differentiate between vegetative and non-vegetative periods (Figure 5c). According to the user feedback, multi-temporal maps may be crucial for performing correlation analyses with climate-related variables (i.e. air temperature, land surface temperature, and radiant temperature), with two-fold benefit. Firstly, correlation results may be used to calibrate or validate local-scale climate models. Secondly, they could be beneficial to assess the effect of urban planning interventions on the local climate. Regarding the format of distribution of these maps, a raster format was mainly indicated (Figure 5d).

In view of the above requirements, in the frame of the LCZ-ODC project LCZ maps are being produced with either monthly or seasonal frequency, mainly depending on the availability of

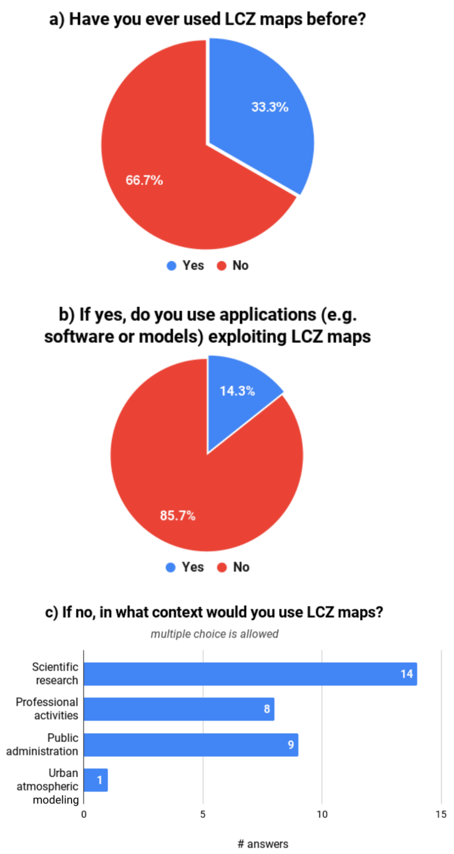

Figure 4. Usage of LCZ maps among the stakeholders.

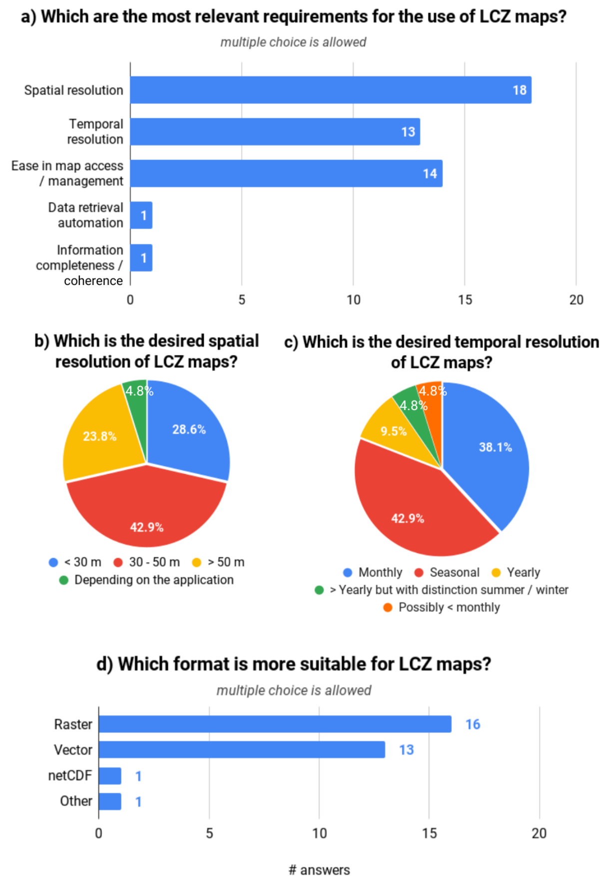

Figure 5. User requirements regarding resolution and format of the LCZ maps.

cloud-free satellite acquisitions and satellite revisit time. Considering the characteristics of the two satellite sensors exploited in the project, i.e. those onboard PRISMA and Sentinel-2 satellites, multi-resolution maps will be produced and provided with the aim of fulfilling the different end-user requirements.

Furthermore, the usability of the maps and products generated within the project will be fostered through interactive interfaces (i.e. Jupyter Notebooks) enabling various operations, including spatial and temporal resolution selection as well as map visualization and downloading. Notebooks will also provide ready-to-use code for expert users to work with, allowing for an easy interaction with the products indexed within the ODC. LCZ maps will be distributed in raster format (e.g. GeoTIFF and NetCDF), in accordance with the characteristics of the ODC software. However, the automatic conversion to vector format will be allowed as an additional feature facilitating the direct use of LCZ maps depending on the specific requirements and analysis tasks.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we illustrate the work carried out in the initial stage of the LCZ-ODC project, which aims to develop a novel methodology for LCZ mapping by leveraging cutting-edge geospatial data and technologies. In the frame of the project, LCZ maps are being produced through the integration of multi-resolution satellite imagery and multiple geospatial layers within an ODC environment. A user-driven approach is followed to ensure that the generated LCZ maps are easily exploitable while fulfilling various end-users' requirements.

In view of the above, a survey was carried out among potential project stakeholders to gather user feedback, which will be considered in the project's development phase to enhance the usability of the generated outputs. The survey results pointed out that ease in map accessibility and pertinent spatial and temporal resolutions are crucial features to be considered for map development and distribution. Specifically, different resolutions and formats are required for the different application tasks.

To facilitate map accessibility and analysis, interactive Jupyter Notebooks will be made available, ensuring ease of use and allowing expert users to conduct in-depth analyses. Moreover, the project will develop multi-resolution and multi-temporal maps to accommodate the diverse requirements of users across different domains.

Further surveys are currently underway to expand the user spectrum and augment the associated sample size, gathering additional feedback as the project progresses towards the validation phases. The iterative process of gathering user feedback and refining the project outputs will contribute to their continuous amelioration to serve the needs of the user community.

6. ACKNOWLEDGMENTS

This work was developed within the LCZ-ODC project, funded by the Italian Space Agency (agreement n. 2022-30-HH.0).

This work has also been carried out in the frame of a Ph.D. Program in Environmental and Infrastructure Engineering, funded by the PON (Programma Operativo Nazionale) project scholarship entitled ”Geospatial Enablement for Climate Change Impact Mitigation on Cities and Urban Resilience Acceleration”.

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